TOMORROW starts here.

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The Internet of Things: Routing and Related Protocols

BRKSPG-1640

Jeff Apcar

Distinguished Services Engineer

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A place for everything and everything in its place.

The Naughty Girl Won, Religious Tract Society, circa 1799

A network for everything and everything in its network.

Me, Just Then

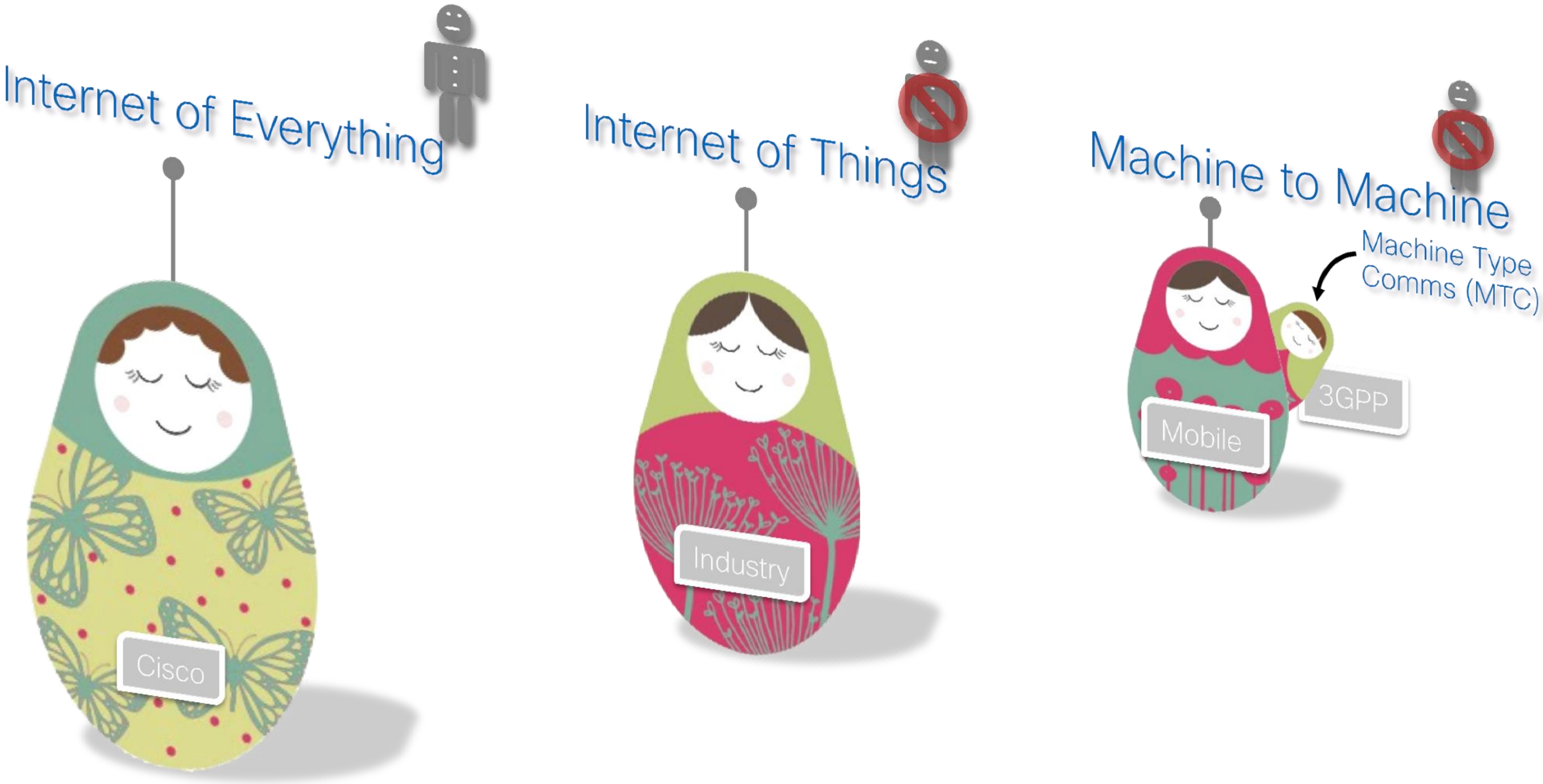
Agenda


What is IoT
Characteristics of IoT Devices
Link Layers LLNs
6LowPAN CoAP RPL
Advanced Metering Example
Vulture scale of complexity and confusion




What is IoT?

Relationships

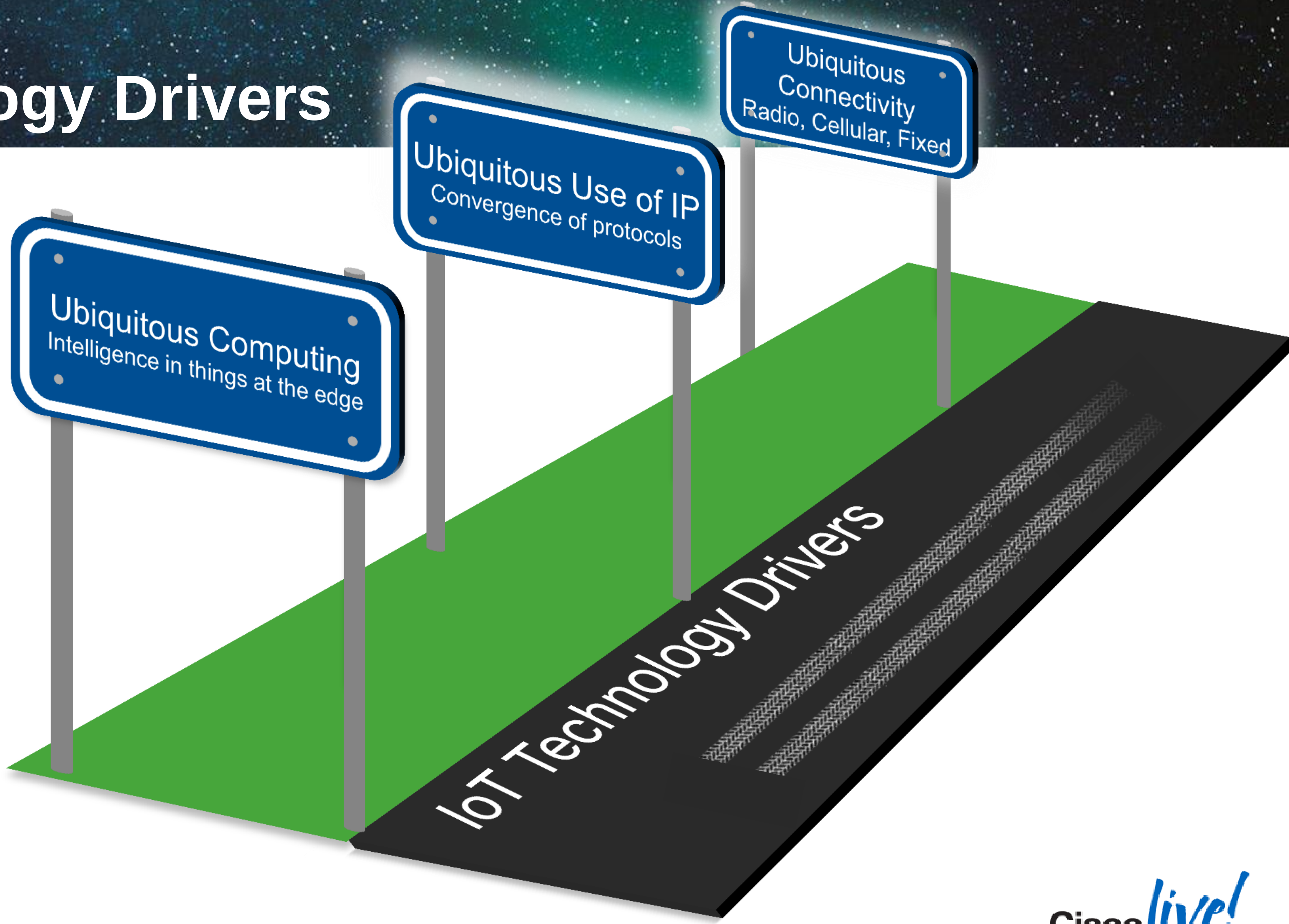


IoT Definition

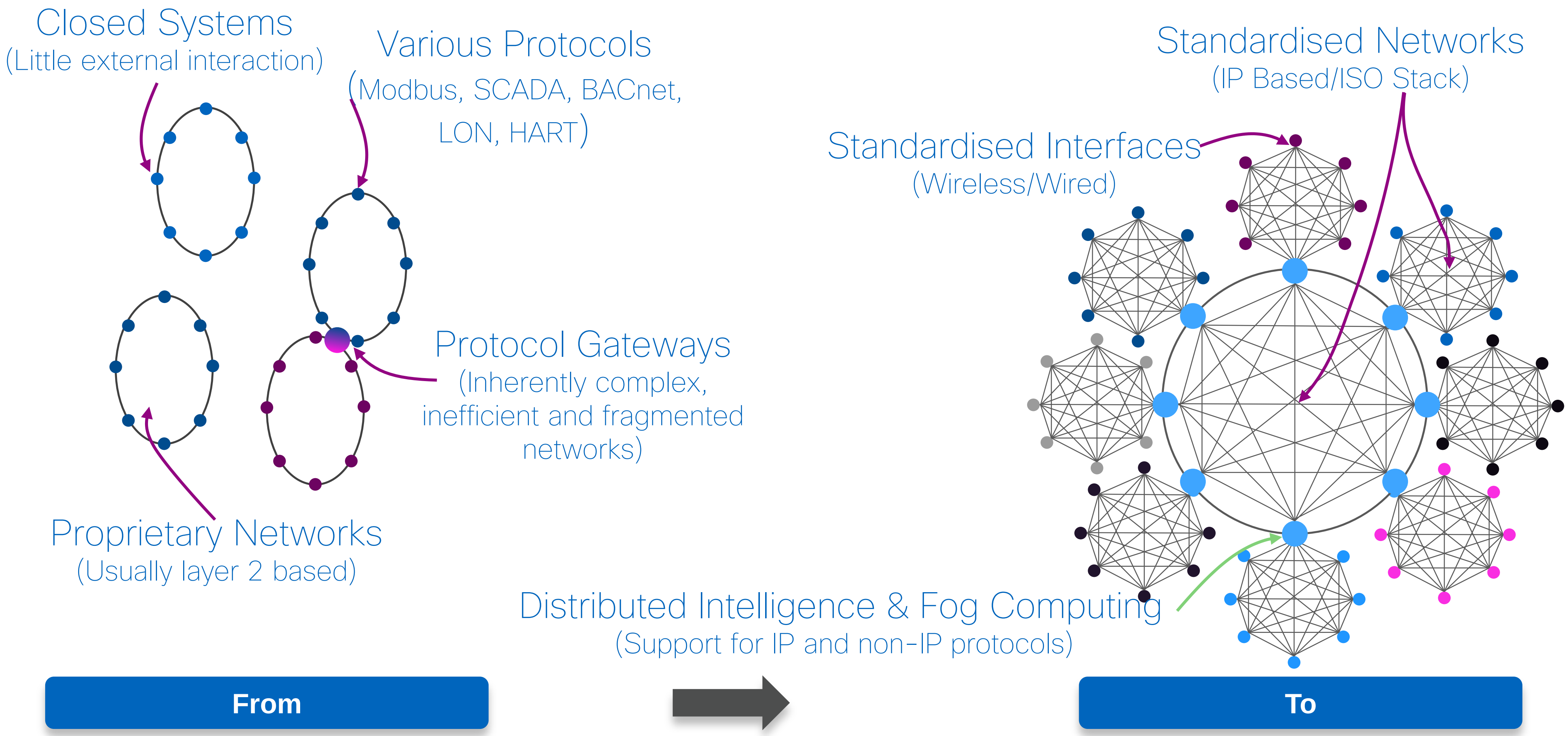
"A pervasive and ubiquitous network which enables monitoring and control of the physical environment by collecting, processing, and analysing the data generated by sensors or smart objects**"

** A collection of "things"

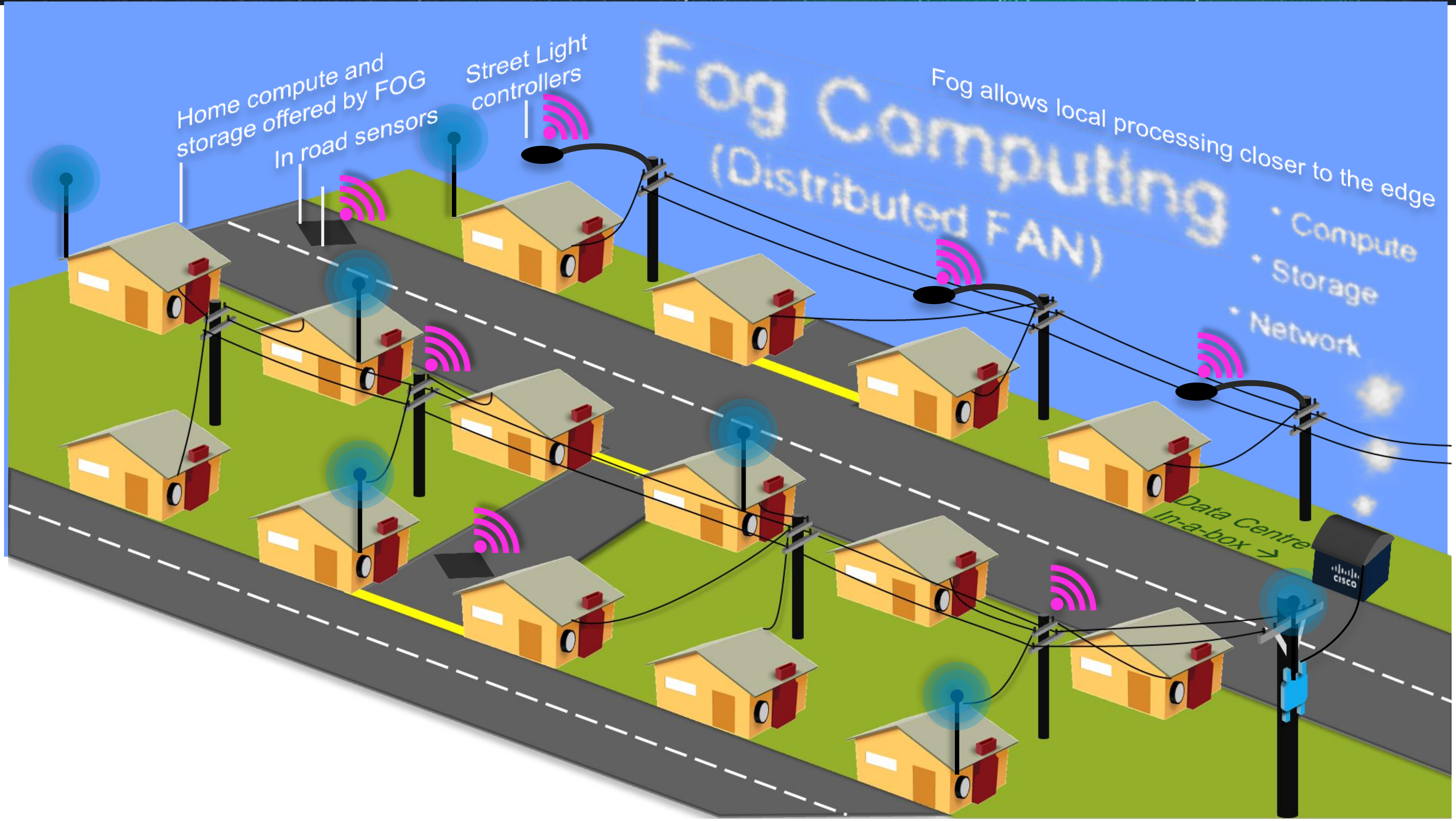
IoT Technology Drivers



IoT Architectural Philosophy



What Is Fog Computing?

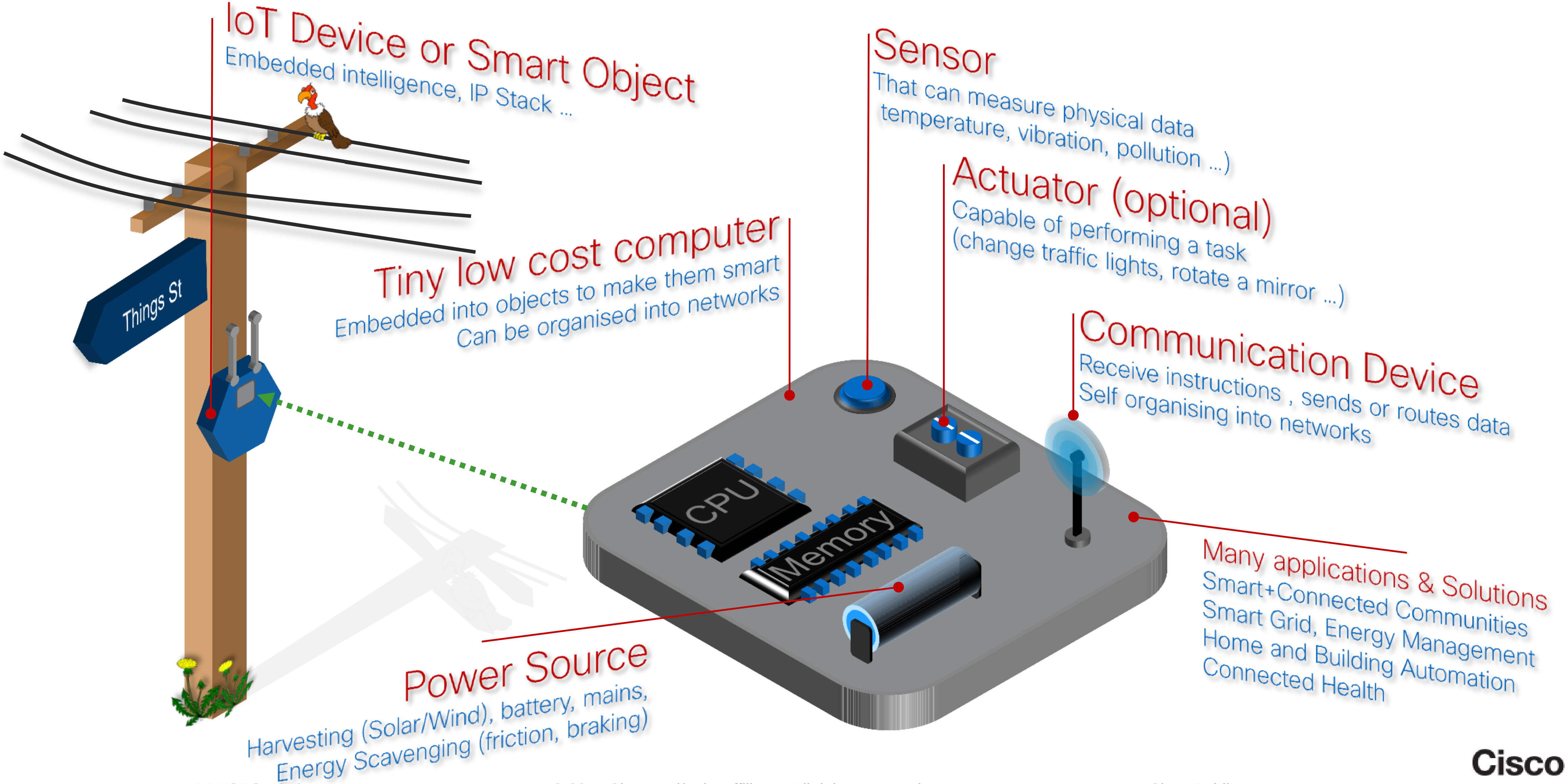




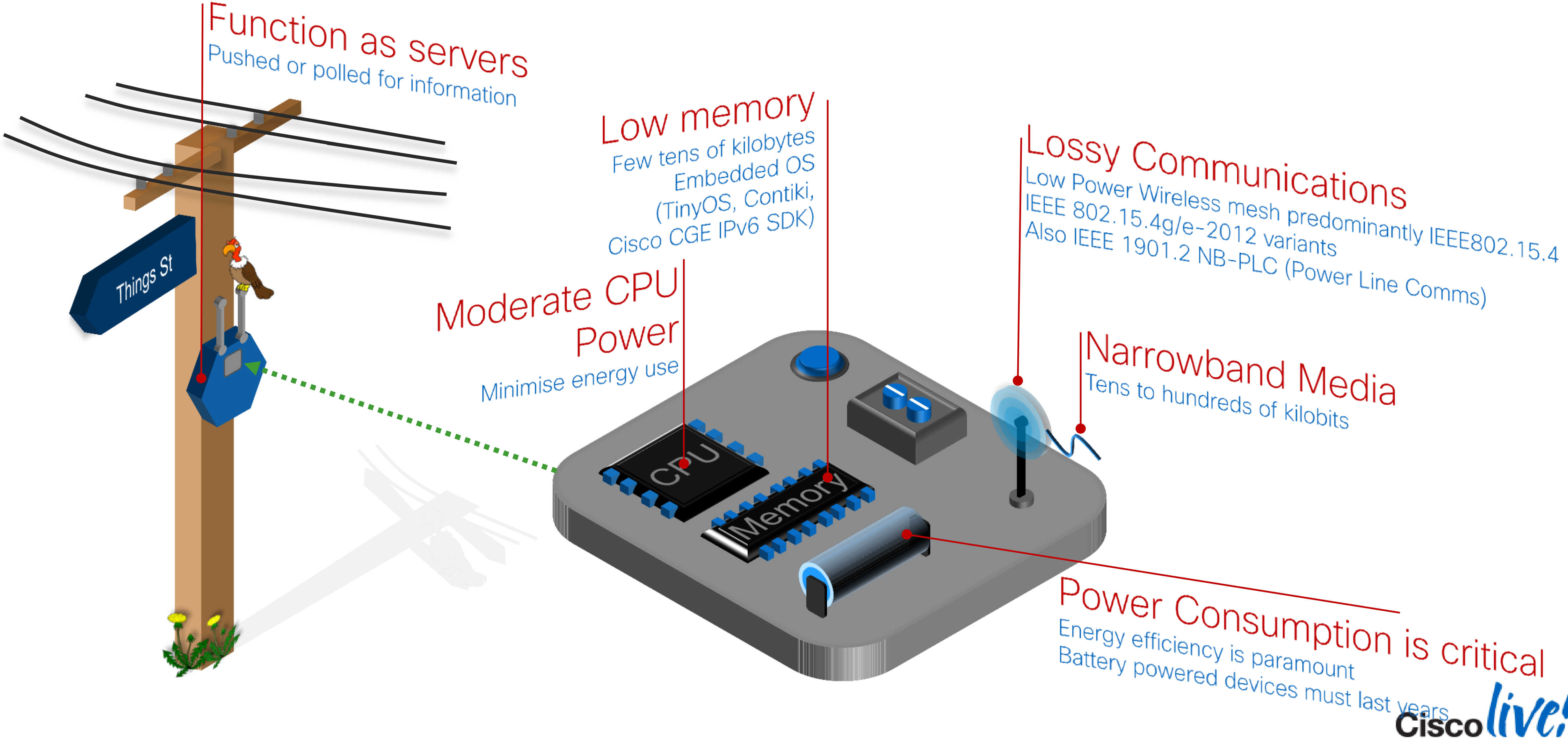

Characteristics IoT Devices

(Smart Objects, “Things” or “Motes”)

IoT Device Characteristics



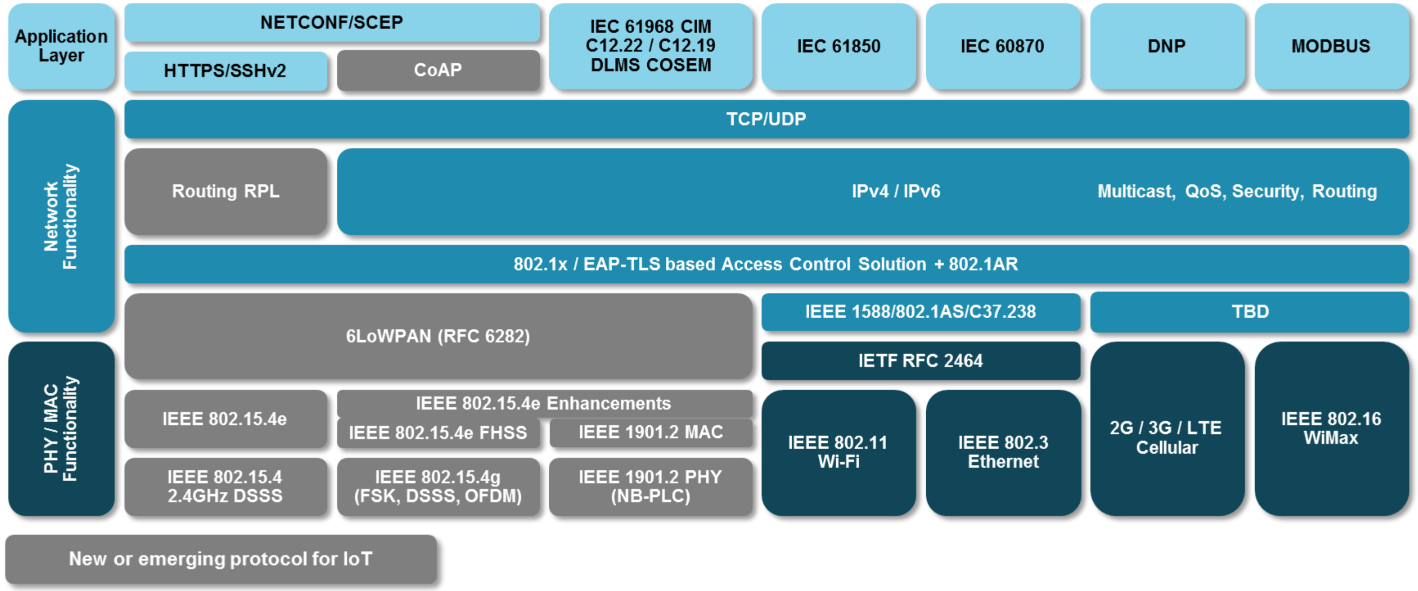
Assumptions & Constraints for Protocols

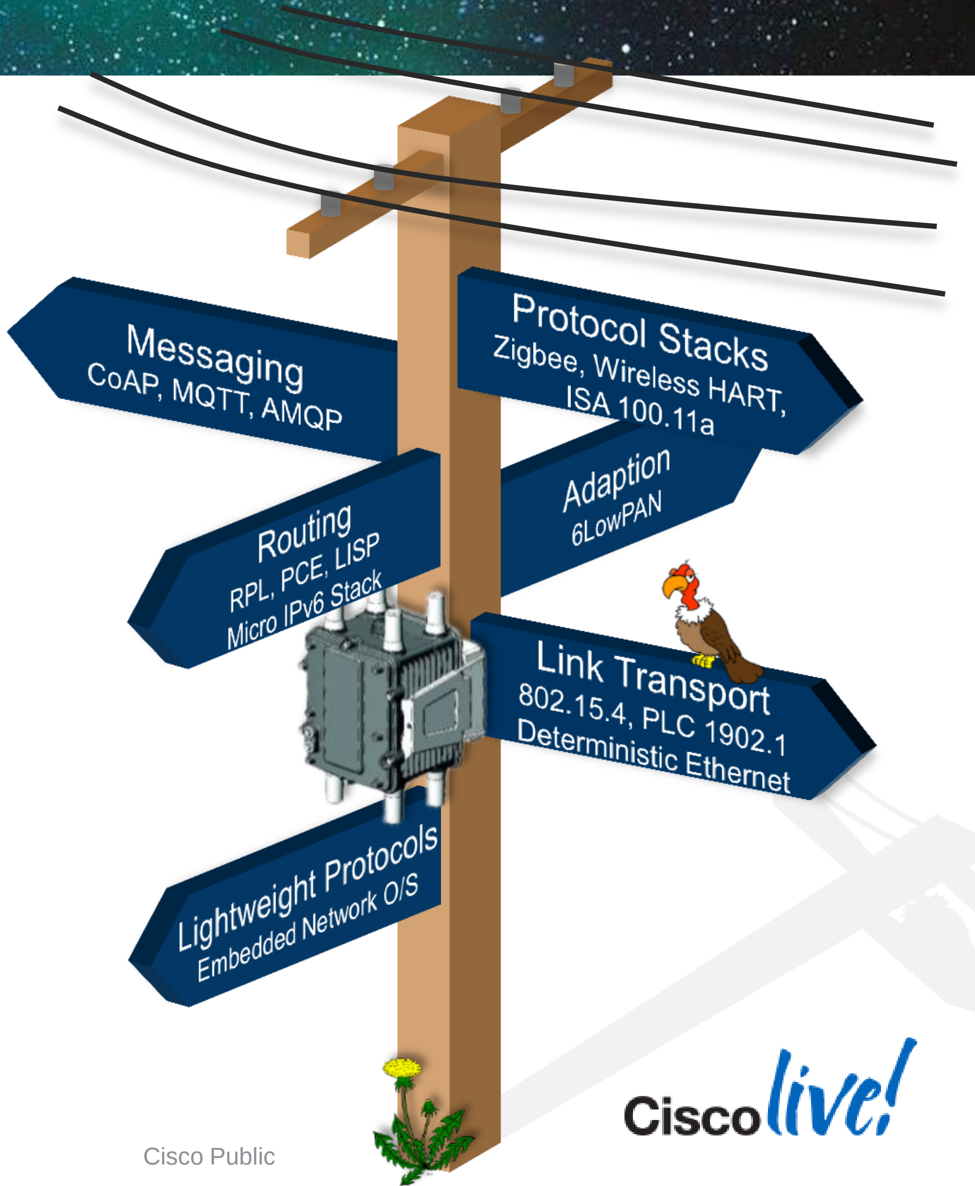


Technologies for IoT Networks

Various Protocols Applied to IoT Networks

- Relevant Protocols for different layers
  - Link Layer (eg., 802.15.4, PLC)
  - Adaption Layer (6LowPAN)
  - Routing (eg., RPL)
  - Messaging (eg., CoAP)
  - Security: (D)TLS, 802.1AR, 802.1X

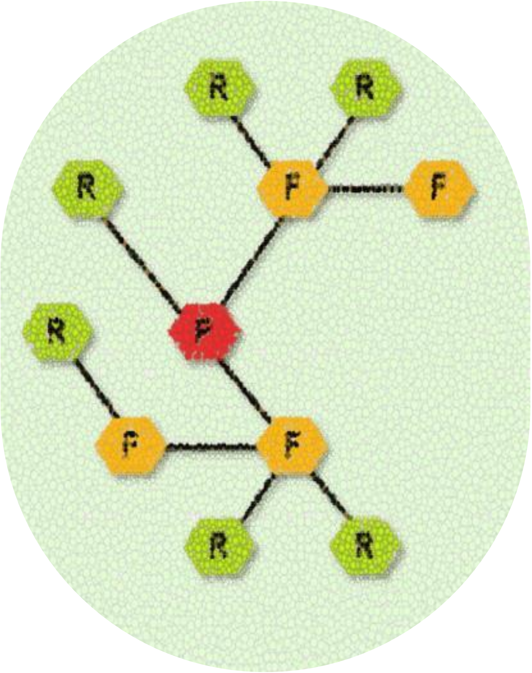







[Some Relevant]

Link Layers



Link Layer – IEEE 802.15.4 (RF Mesh)

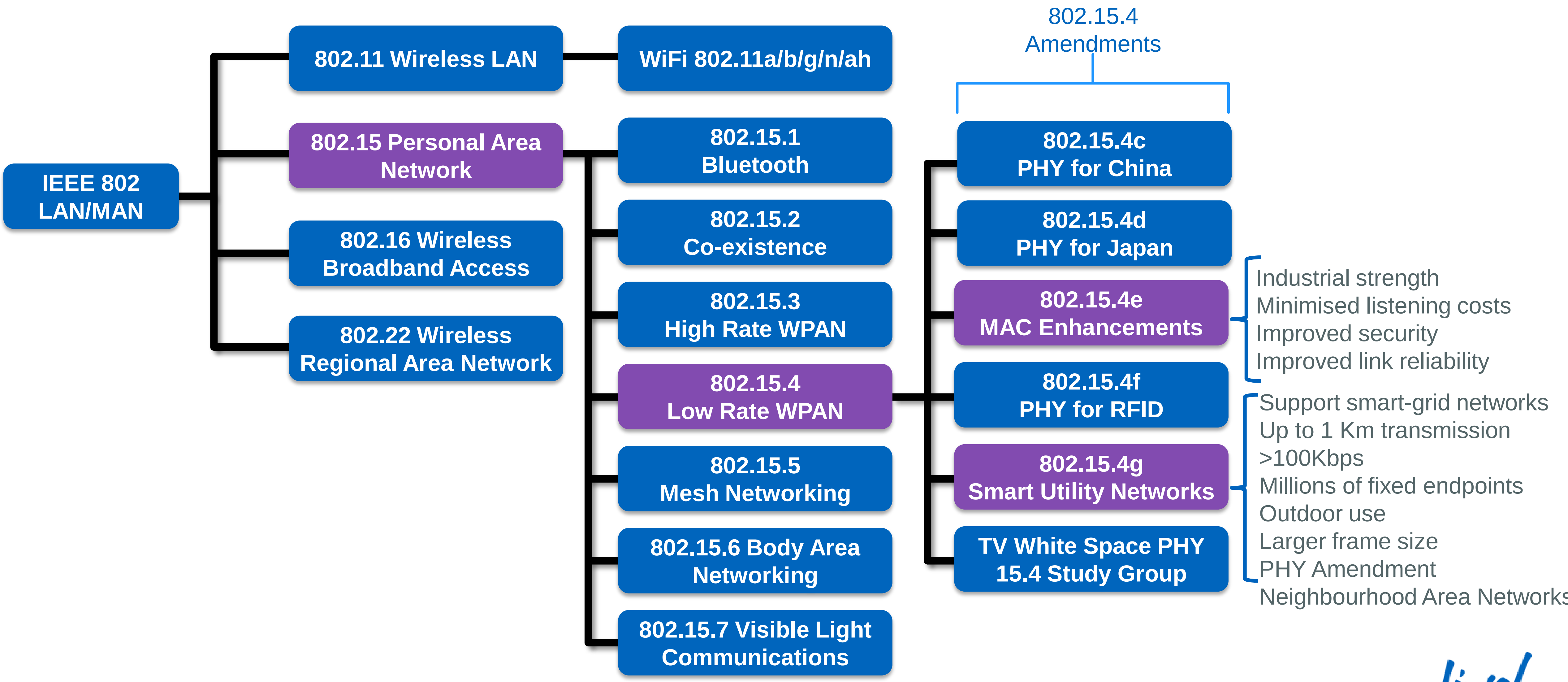
IEEE 802.15.4 Overview

- Initial activities focused on wearable devices "Personal Area Networks"
- Activities have proven to be much more diverse and varied
  - Data rates from Kb/s to Gb/s
  - Ranges from tens of metres up to a Kilometre
  - Frequencies from MHz to THz
  - Various applications not necessarily IP based
- Focus is on "specialty", typically short range, communications
  - If it is wireless and not a LAN, MAN, RAN, or WAN, it is likely to be 802.15 (PAN)
- Foundation for several protocol stacks
  - Zigbee, Zigbee RF4CE, Zigbee Pro, Wireless HART,
  - ISA 100.11a, RPL

IEEE 802.15 WPAN™ Task Group 4 (TG4) Charter

"The IEEE 802.15 TG4 was chartered to investigate a low data rate solution with multi-month to multi-year battery life and very low complexity. It is operating in an unlicensed, international frequency band. Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation."

IEEE Wireless Standards

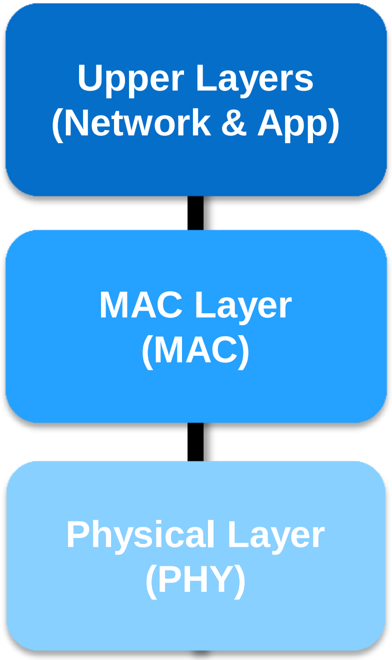


IEEE 802.15.4 (Base Standard)

- Designed for low bandwidth, low transmit power, small frame size
  - More limited than other WPAN technologies such as Bluetooth
  - Basic packet size is 127 bytes (802.15.4g is up to 2047 bytes) (Smaller packets, less errors)
  - Transmission Range varies (802.15.4g is up to 1km)
- Fully acknowledged protocol for transfer reliability
  - Considered a lossy protocol (subject to interference etc…)
- Data rates of 851, 250, 100, 40 and 20 kbps (IEEE 802.15.4-2011 05-Sep-2011)
  - Frequency and coding dependent
- Two addressing modes; 16-bit short (local allocation) and 64-bit IEEE (unique global)
- Several frequency bands (Different PHYs)
  - Europe 868-868.8 MHz 3 chans , USA 902-928 MHz 30 chans, World 2400-2483.5 MHz 16 chans
  - China - 314–316 MHz, 430–434 MHz, and 779–787 MHz Japan - 920 MHz
- Security Modes: None, ACL only, Secured Mode (using CCM* for AES IEEE 802.15.4-2006 /2011)

802.15.4 Protocol Stack

- Specifies PHY and MAC only
- Medium Access Control Sub-Layer (MAC)
  - Responsible for reliable communication between two devices
  - Data framing and validation of RX frames
  - Device addressing
  - Channel access management
  - Device association/disassociation
  - Sending ACK frames
- Physical Layer (PHY)
  - Provides bit stream air transmission
  - Activation/Deactivation of radio transceiver
  - Frequency channel tuning
  - Carrier sensing (CSMA/CA)
  - Received signal strength indication (RSSI)
  - Link Quality Indicator (LQI)
  - Data coding and modulation, Error correction



IEEE 802.15.4e

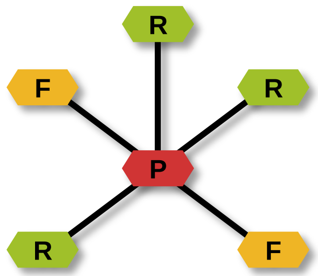
- Amendment to the 802.15.4-2006 MAC needed for the applications served by
  – 802.15.4f PHY Amendment for Active RFID
  – 802.15.4g PHY Amendment for Smart Utility Networks
  – Industrial applications (such as those addressed by HART 7 and the ISA100 standards)
- Security: support for secured ack
- Low Energy MAC extension
  – Coordinated Sampled Listening (CSL)
- Channel Hopping
  – Not built-in, subject to vendor design
- New Frame Types
  – Enhanced (secure) Acknowledgement (EACK)
  – Enhanced Beacon and Beacon Request (EB and EBR)
  – Information Elements (IE) support (carries SSID, time, other protocol information)

IEEE 802.15.4 vs IEEE 802.15.4g/e Comparison

	IEEE 802.15.4	IEEE 802.15.4g/e	Comments
Frequency bands	868 MHz 1-3 channels 915 MHz 10-30 channels 2450 MHz 16 channels	(*) 169, 450-470, 470-510, 863-870, 1427-1518 MHz	• Frequency bands availability per region/country • # channels: 802.15.4-2003 – 802.15.4-2006 • 802.15-4-2011: 314–316, 430–434 and 779–787 MHz bands for China (*) in addition of 802.15.4-2011 frequency bands
Modulation	BPSK, ASK (Sub-GHz) O-QPSK (2.4GHz)	MR-FSK, MR-OFDM and MR-O-QPSK	BPSK/O-QPSK in 802.15.4-2003 802.15.4-2011 adds modulations 802.15.4g add 3 new PHY SUN modulation
Data Rate	Up to 20, 40 and 250 kb/s	Up to 800 kb/s (OFDM)	Frequency band and modulation dependent
Maximum PSDU size	127 bytes	2047 bytes	Better aligned with IP MTU
FCS	16 bits	32 bits	Better error protection
Information Elements	No	Yes, 15.4e	Allow vendor specific information
PAN ID	0-65534		Identifies a WPAN
MAC Address	16 bits or 64 bits		16 bits = locally managed, 64 bits = EUI-64

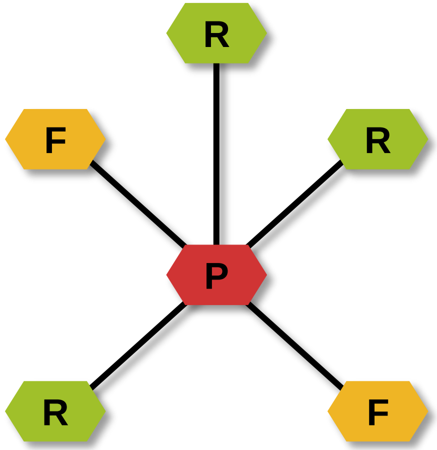
IEEE 802.15.4 Node Types

- Full Function Device (FFD)
  - Can operate as a PAN co-ordinator (allocates local addresses, gateway to other PANs)
  - Can communicate with any other device (FFD or RFD)
  - Ability to relay messages (PAN co-ordinator)
- Reduced Function Device (RFD)
  - Very simple device, modest resource requirements
  - Can only communicate with FFD
  - Intended for extremely simple applications



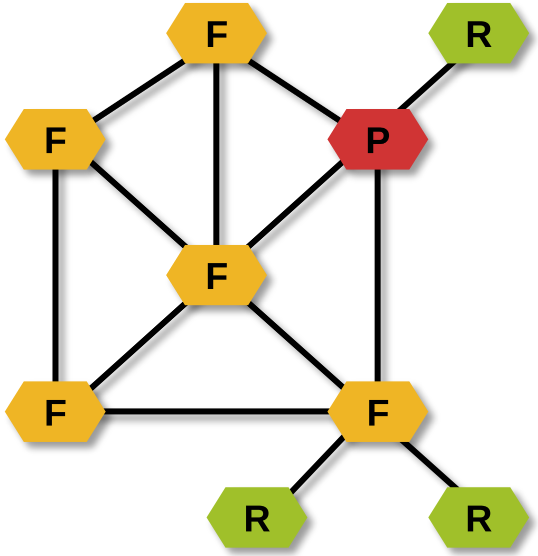
IEEE 802.15.4 Topologies

- Star Topology



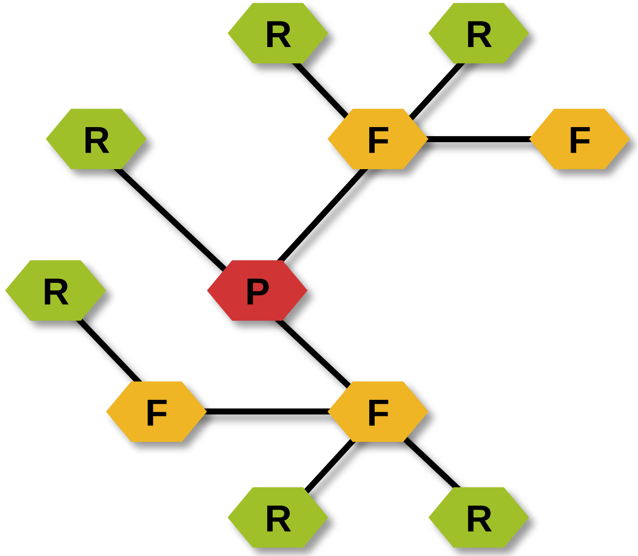
- All devices communicate to PAN co-ordinator which uses mains power
- Other devices can be battery/scavenger/harvest

- Mesh Topology



- Devices can communicate directly if within range

- Cluster Tree



- Higher layer protocols like RPL may create their own topology that do not follow 802.15.4 topologies

Single PAN co-ordinator exists for all topologies, Layer 2

Link Layer – IEEE 1901.2 NB-PLC

IEEE 1901.2 NB-PLC Overview

- Defines PHY & MAC layers for narrow band power line comms (NB-PLC)
  - Based on P1901-2010 standard for broadband over power line (BPL) networks
- Various use cases
  - Grid control, electric vehicle to charging station, street lighting, household power plugs, solar devices
- Operating Parameters
  - Transmission frequency < 500Khz, Data rates up to 500Kbps
  - Transmission over low voltage (< 1000V meter to transformer) and medium voltage (1000V – 72kV)

Power Line Comms (PLC) Standards

HomePlug Alliance

IEEE 1901 PLC

- **P1901-2010 Broadband over PLC**
  - Based on HomePlug AV specification (up to 500Mbps)
  - Multimedia communications, in-home devices
- **1901.2 Low Frequency Narrow Band PLC**
  - SmartGrid, utility meter, urban, industrial and long range (500Kbps)

The IEEE 1901.2 standard specifies communications for low frequency (less than 500 kHz) narrowband power line devices via alternating current and direct current electric power lines. This standard supports indoor and outdoor communications over low voltage line (line between transformer and meter, less than 1000 V), through transformer low-voltage to medium-voltage (1000 V up to 72 kV) and through transformer medium-voltage to low-voltage power lines in both urban and in long distance (multi- kilometre) rural communications.

HomeGrid Forum

ITU G.hn PLC

- **G.9960 Physical Layer**
- **G.9961 Link Layer**

G3-PLC Alliance → **G.9903 G3-PLC**

PRIME ALLIANCE → **G.9904 PRIME**

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IEEE P1901.2 NB-PLC Features

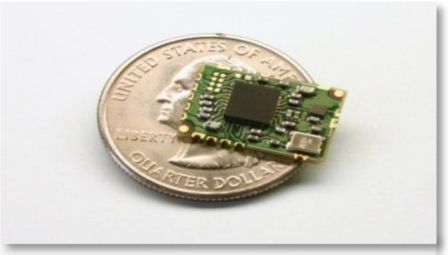
- Operates over AC/DC power lines
- Uses techniques borrowed from RF communications
  - Mitigate interference and noise from lack of cable isolation and shielding
  - Addresses large variation in channel characteristics
- Aligned with IEEE 802.15.4g/e RF Mesh profile
  - Uses IEEE 802.15.4g/e MAC (not limited to 127 bytes, support Information Elements)
  - Supports Information Elements (IE) as per 802.15.4.e
  - 6LoWPAN (RFC 6282) as adaptation layer and RPL for routing (RFC 6550) – IPv6 support
- CSMA/CA – Slotted/unslotted
- OFDM PHY
- Supports IEEE 802.15.4 security

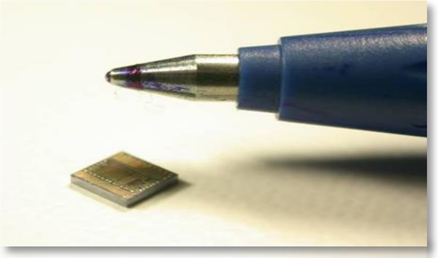
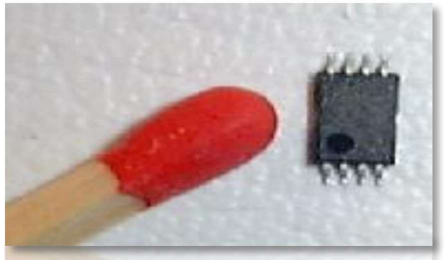



Low Power Lossy Networks

What is a Low Power Lossy Network (LLN)?

- LLNs comprise a large number of highly constrained devices (smart objects) interconnected by predominantly wireless links of unpredictable quality
- LLNs cover a wide scope of applications
  - Industrial Monitoring, Building Automation, Connected Home, Healthcare, Environmental Monitoring, Urban Sensor Networks, Energy Management, Asset Tracking, Refrigeration
- Several IETF working groups and Industry Alliance addressing LLNs
  - IETF - CoRE, 6Lowpan, ROLL
  - Alliances - IP for Smart Objects Alliance (IPSO)



Characteristics of LLNs

- LLNs operate with a hard, very small bound on state
- LLNs are optimised for saving energy in the majority of cases
- Traffic patterns can be MP2P, P2P and P2MP flows
- Typically LLNs deployed over link layers with restricted frame-sizes
  - Minimise the time a packet is enroute (in the air/on the wire) hence the small frame size
  - The routing protocol for LLNs should be adapted for such links
- Most nodes are asleep and wake up periodically
- LLN routing protocols must consider efficiency versus generality
  - Many LLN nodes do not have resources to waste

IETF LLN Related Workgroups

IETF

- Application
  - Core
- General
- Internet
  - 6LO
  - 6LowPAN
  - LWIG
- Ops and Mgmt
- Routing
  - ROLL
- Security
- Transport

CoAP

Constrained Restful Environments
Charter to provide a framework for resource-oriented applications intended to run on constrained IP networks.

IPv6 over Networks of Resource constrained nodes
IPv6-over-foo adaptation layer specifications using 6LoWPAN technologies (RFC4944, RFC6282, RFC6775) for link layer technologies of interest in constrained node networks. .

6LowPAN

IPv6 over Low power WPAN (6LowPAN)
Charter to develop protocols to support IPv6 over IEEE 802.15.4 low-power radio networks and IEEE 1901.2 Power Line Comms

Lightweight Implementation Guidance
Charter is to provide guidance in building minimal yet interoperable IP-capable devices for the most constrained environments. .

RPL

Routing over Low Power Lossy Networks
Charter focusses on routing issues for low power lossy networks.

Security, Transport: Reuse work done here where possible

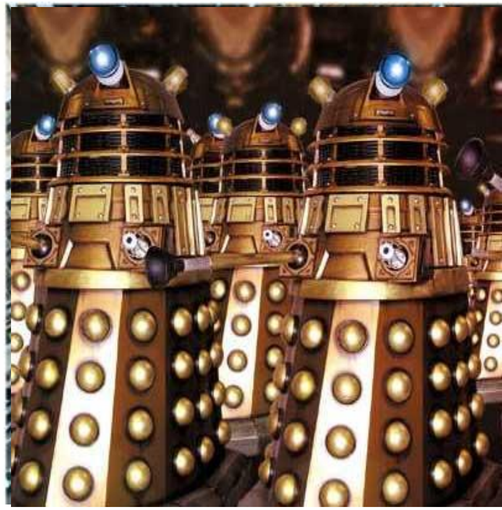
IP for Smart Objects (IPSO) Alliance

- IPSO Alliance formed drive standardisation and inter-operability
  - Create awareness of available and developing technology
- Document use of new IP based smart object technologies
  - Generate tutorials, webinars, white papers and highlight use cases
  - Provide an information repository for interested parties
- Coordinate and combine member marketing efforts
- Support and organise interoperability events
  - COMPLIANCE program (Based on IPv6 forum)
- http://www.ipso-alliance.org

Promoters

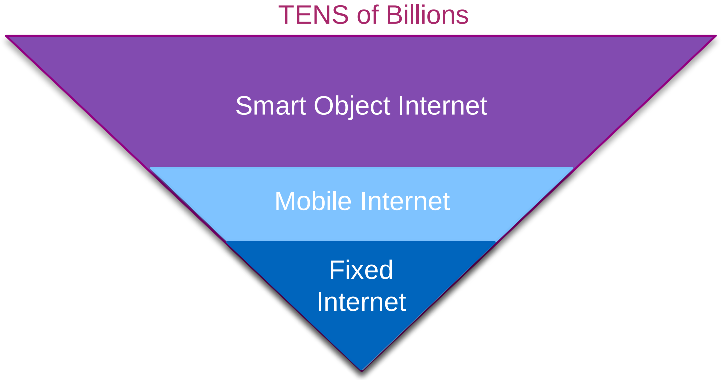
Contributors



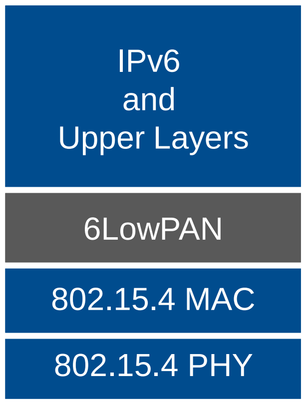
6LoWPAN Adaption Layer

IPv4 or IPv6?



- The current Internet comprises several billion devices
  - Add to this growing 3G, 4G mobile devices
  - There is no scope for IPv4 to support Smart Object Networks
- Not much IPv4 legacy in Smart Object Networks or LLNs
- Smart Objects will add tens of billions of additional devices
- IPv6 is the only viable way forward
  - Solution to address exhaustion
  - Stateless Auto-configuration thanks to Neighbour Discovery Protocol
- Some issues with IPv6 address size
  - Smart Object Networks use low power wireless with small frame size
  - Solution to use stateless and stateful header compression (6LoWPAN)
  - However, IPv6 main header has a fixed size, therefore simpler to compress than IPv4
  - Hence it is preferred IP version standardised at the IETF for these LLN PHY/MAC

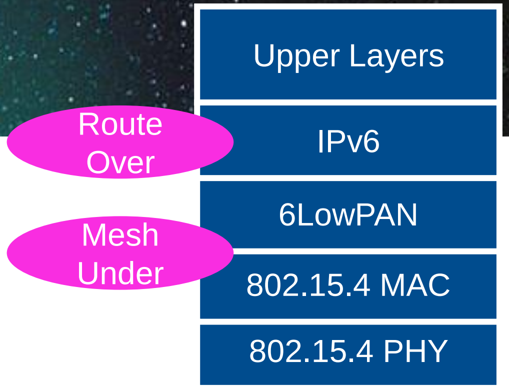
What is 6LoWPAN ? (RFC 6282)



- IPv6 over Low power Wireless Personal Area Networks
  - Initially an adaptation layer for IPv6 over IEEE 802.15.4 links
  - Now used by IEEE P1901.2 (PLC), Bluetooth Low Energy, DECT Ultra Low Energy
- Why do we need an adaption layer?
  - IEEE 802.15.4 MTU originally 127 bytes, IPv6 minimum MTU is 1280 bytes
  - Even though 15.4g enables 2047 byte frame size, however bandwidth optimization is still desired
  - IPv6 does not do fragmentation, left to end nodes or lower layers
- Performs 3 functions each with its own 6LoWPAN header
  - IPv6 Header compression
  - IPv6 packet fragmentation and re-assembly
  - Layer 2 forwarding (also referred to as mesh under)
- RFC4919 - Overview, Assumptions, Problem Statement, and Goals

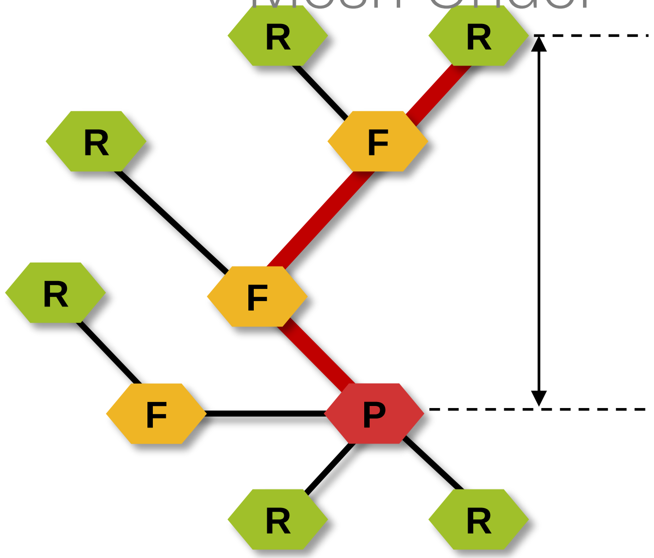
Internet Things go better with IPv6

Mesh Under vs Router Over

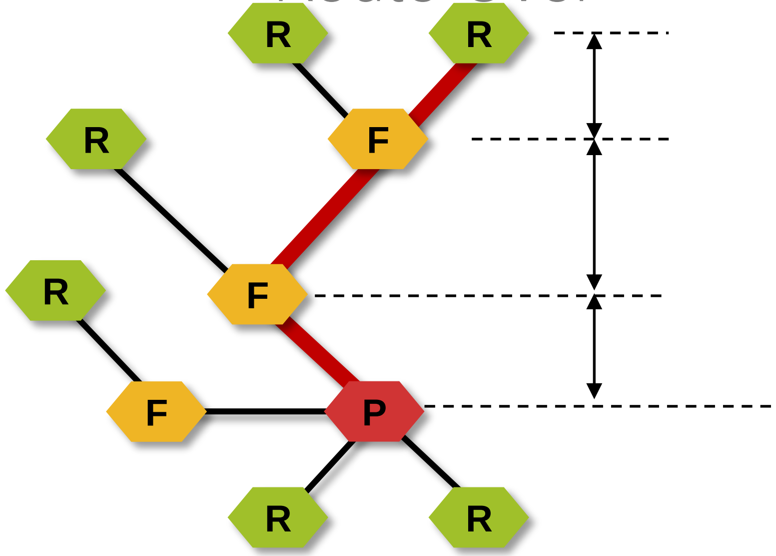


- Mesh Under – No IP routing within PAN
  - Single link-local scope crosses multiple radio links and nodes
  - Adaption layer emulates broadcast link
- Route Over – L3 IP Routing – each node is a router
  - Single link-local scope defined by inherent radio connectivity

Mesh Under

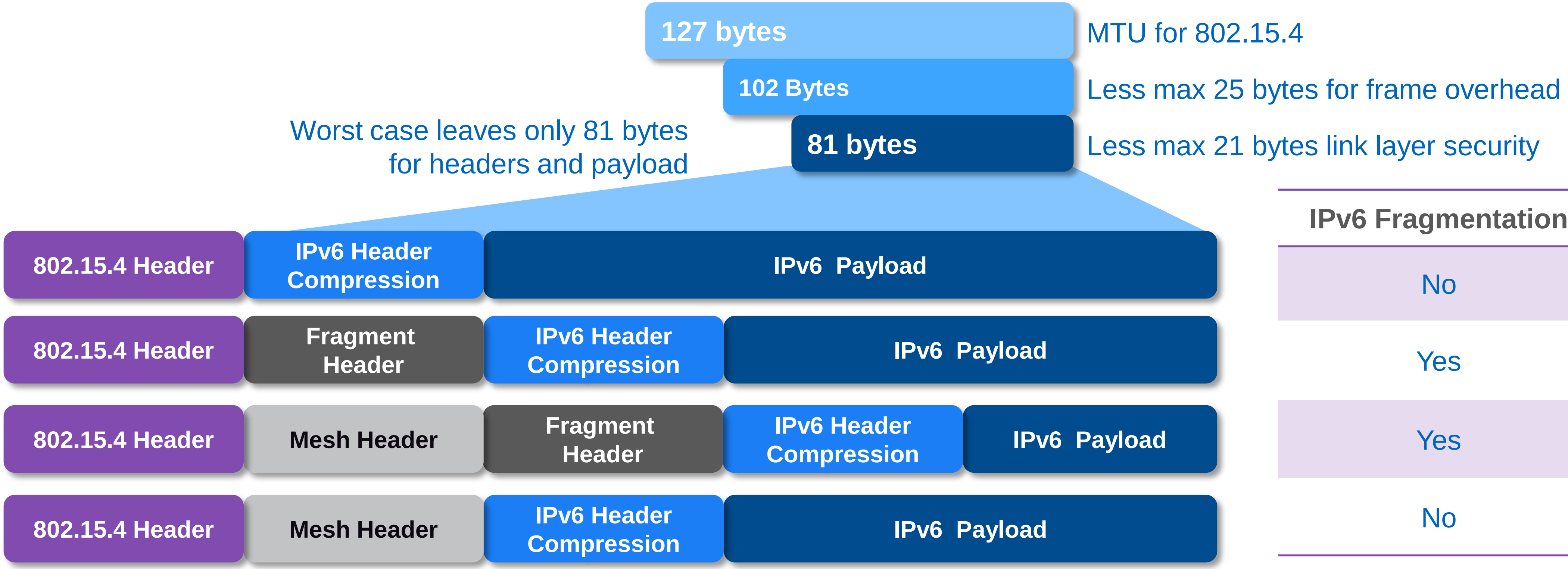


Route Over



6LoWPAN Header Stacks

- Several 6LoWPAN headers are included when necessary
  - IPv6 compression header
  - Fragmentation header (eliminated if single datagram can fit entire IPv6 payload)
  - Mesh or Layer 2 forwarding header (currently not used/implemented)



IPv6 Fragmentation	Multiple L2 Hops
No	No
Yes	No
Yes	Yes (Future)
No	Yes (Future)

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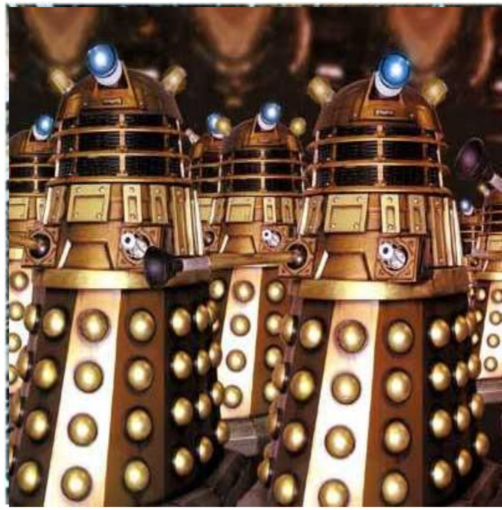
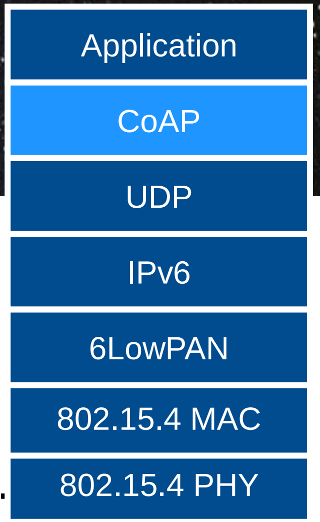
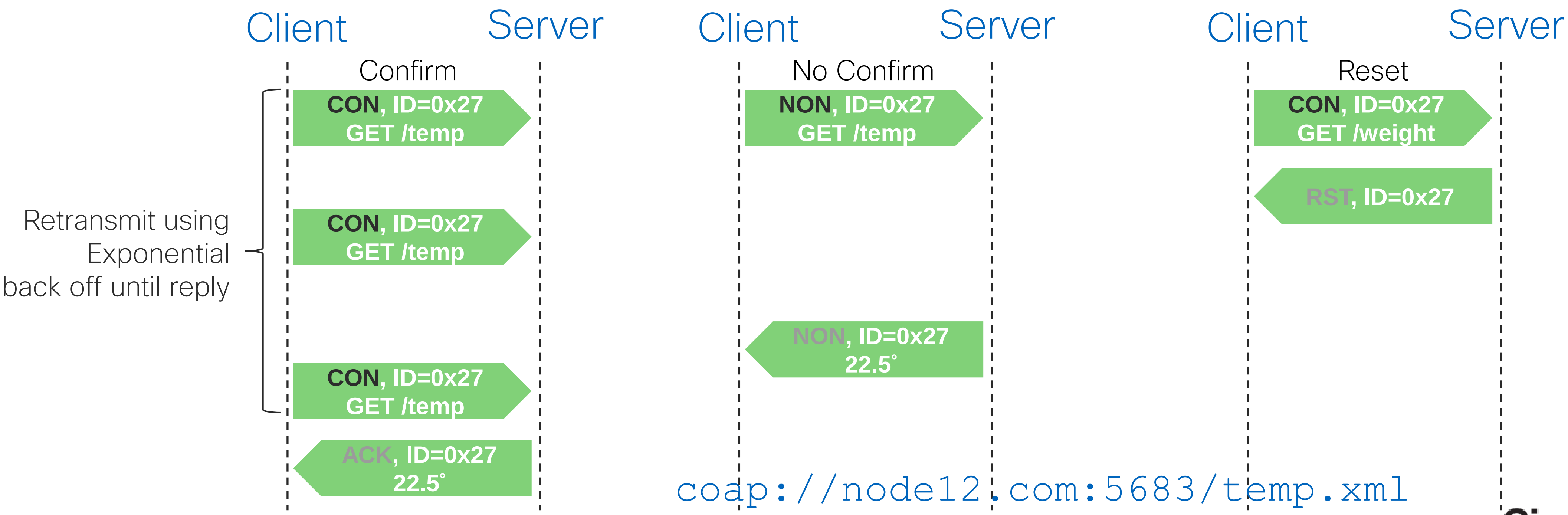


Messaging Protocols

Constrained Application Protocol (CoAP)



- Initial work of CoRE
  - Define a protocol to manipulate resources on constrained devices
- The result is CoAP IETF draft https://ietf.org/doc/draft-ietf-core-coap/
  - Lightweight version of HTTP for constrained environment (GET, PUT, POST, DELETE…
  - Datagram (UDP) based, Request/Response model, Proxy-mode support, Reliable Delivery



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ROLL Working Group

What is ROLL?

- Routing Over Low power and Lossy Networks (2008)
  - http://www.ietf.org/html.charters/roll-charter.html
- Mission: To define routing solutions for LLNs
- Application specific LLN routing RFC have been developed

RFC	Application	Title
RFC 5673	Industrial	Industrial Routing Requirements in Low-Power and Lossy Networks
RFC 5548	Urban	Routing Requirements for Urban Low-Power and Lossy Networks
RFC 5826	Home	Home Automation Routing Requirements in Low-Power and Lossy Networks
RFC 5867	Building	Building Automation Routing Requirements in Low-Power and Lossy Networks

- Specifying the routing protocol for smart object networks
  - Routing Protocol for LLNs (RPL) currently WG document

Where Should Routing Take Place ?

- Historically, a number of interesting research initiatives on WSN
  – Work on Wireless Sensors Network focussed on algorithms … not architecture
- Most work assumed the use of MAC addresses
  – Layer 2 “routing” (mesh-under)
- Support of multiple PHY/MAC is a MUST
  – IEEE 802.15.4, Low Power Wifi, Power Line Communications (PLC)
- Use IP to route
  – Supports multiple PHY/MAC
  – Moves from mesh-under (L2) to router-over(L3)

Characteristics of Internet vs Sensor Networks

Current Internet	Sensor Networks
Nodes are routers	Nodes are sensor/actuators and routers
IGP with typically few hundreds of 100 nodes	An order of magnitude larger in nodes
Links and Nodes are stable	Links are highly unstable Nodes fail more frequently
Node and link bandwidth constraints are generally non-issues	Nodes & links are high constrained
Routing is not application aware	Application-aware routing, in-Band processing is a MUST

Technical Challenges for Routing Protocols

- Energy consumption is a major issue (battery powered sensors/actuators)
- Limited processing power
- Very dynamic topologies
  - Link failure
  - Node failures (triggered or non triggered)
  - Node mobility (in some environments)
- Data processing usually required on the node itself
- Sometimes deployed in harsh environments (Industrial)
- Potentially deployed at very large scale (millions of nodes)
- Must be self-managed (auto-discovery, self-organising networks)

Current Routing Protocols

- The current IGPs (OSPF, ISIS) rely upon static link metrics
  - Used to create best/shortest path to destination
  - No account taken of node/router status (high CPU, hardware failures)
- Not suitable for the dynamic nature of an LLN with many variables
  - Wireless Signal Strength and Quality
  - Node resources such as residual energy
  - Link throughput and reliability
- IGP needs the ability to consider different metric/constraint categories
  - Node vs Links
  - Qualitative vs Quantitative
  - Dynamic vs Static




Routing Over Low Power Lossy Networks (RPL)

RPL - Routing Protocol for LLNs

- RPL is an extensible proactive IPv6 distance vector protocol
  - Developed for mesh routing environments
  - Builds a Destination Oriented Directed Acyclic Graph (DODAG) based on an objective
  - RPL supports shortest-path constraint based routing applied to both links and nodes
  - Supports MP2P, P2MP and P2P between devices (leaves) and a root (border router)
- RPL specifically designed for "Lossy" networks
  - Agnostic to underlying link layer technologies (802.15.4, PLC, Low Power Wireless)
  - RFC 6550: RPL: IPv6 Routing Protocol for LLNs
  - RFC 6551: Routing Metrics Used for Path Calculation in LLNs
  - RFC 6552: Objective Function Zero for the Routing Protocol for LLNs
  - RFC 6553: RPL Option for Carrying RPL Information in Data-Plane Datagrams
  - RFC 6554: An IPv6 Routing Header for Source Routes with RPL
  - RFC 6206: The trickle algorithm
  - RFC 6719: The Minimum Rank with Hysteresis Objective Function

RPL is pronounced "Ripple"

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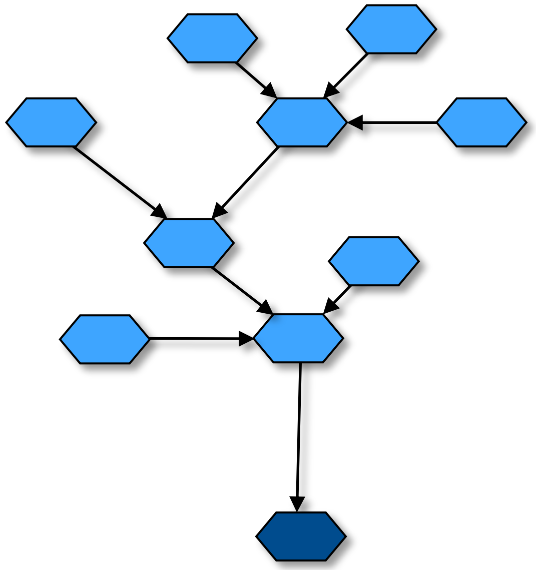


What is a DAG?

Directed Acyclic Graph

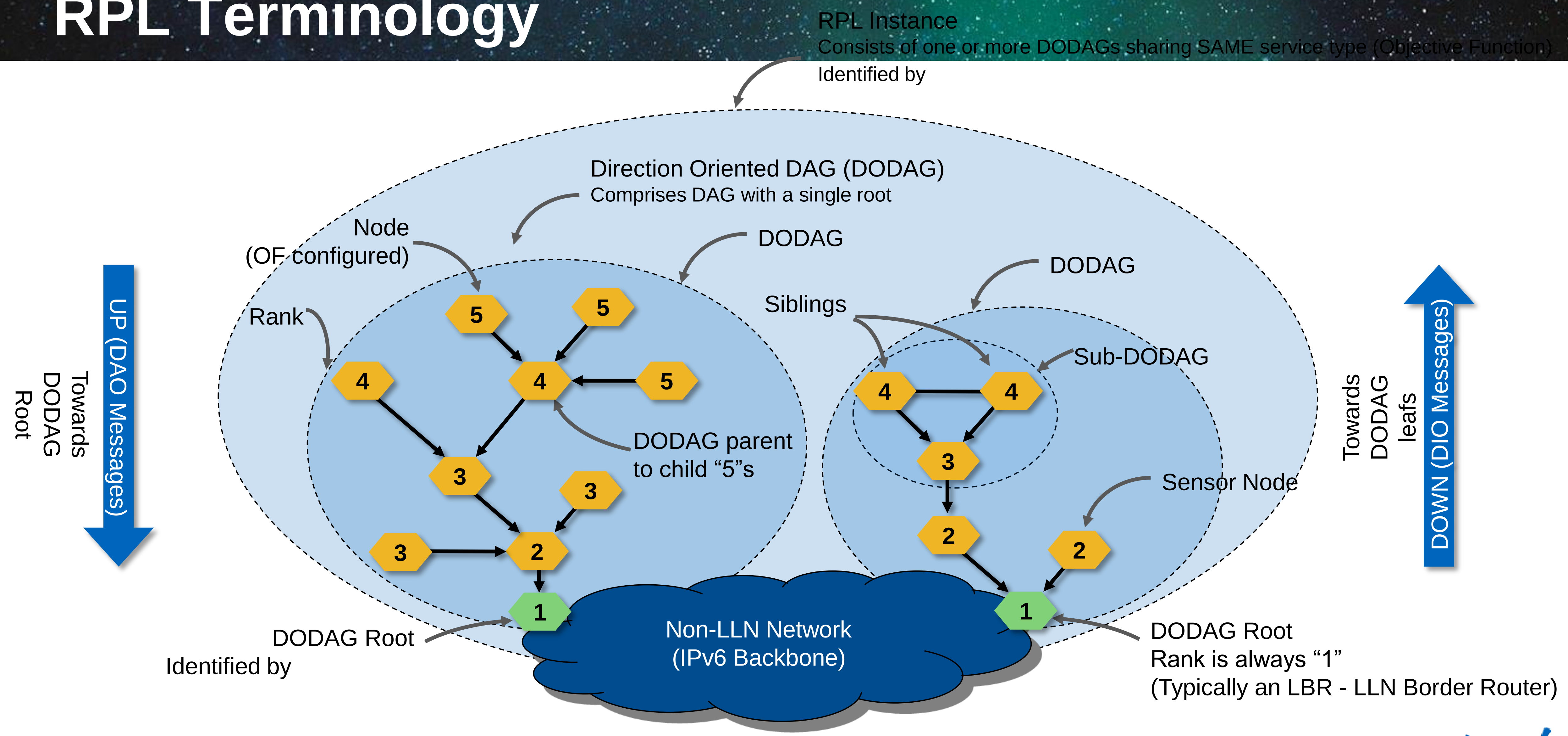
In the context of routing, a DAG is formed by a collection of vertices (nodes) and edges (links).

Each edge connecting one node to another (directed) in such a way that it is not possible to start at Node X and follow a directed path that cycles back to Node X (acyclic).

A Destination Oriented DAG is a DAG that comprises a single root node.

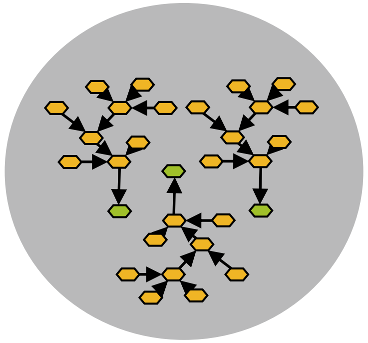
IT IS A WAY TO CREATE A LOOP FREE PATH

RPL Terminology



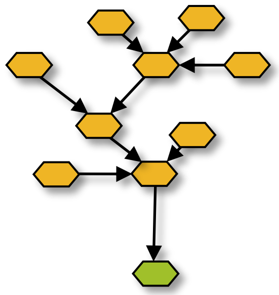
RPL Instances

- RPL can form multiple instances
  - Each instance honours a particular routing objective/constraint
  - Instance consists one or more DODAGs derived from the same OBJECTIVE FUNCTION
  - Nodes select a parent (towards root) based on metric, OF and loop avoidance
- Allows upwards and downwards routing (from DODAG root)
- Trickle timers are used to suppress redundant messages
  - Saves on energy and bandwidth (Like OSPF exponential backoff)
- Under-react is the rule
  - Local repair preferred versus global repair to cope with transient failures



RPL DODAGs

- RPL enables nodes to discover each other and form DODAGs
  - Uses ICMPv6 control messages with RPL message codes
- Each root uses a unique DODAG ID (IPv6 address) to identify itself within an RPL Instance
- Routing is performed over the DODAG using distance vector techniques
- Every hop to the root MUST have an alternate path
  - (Quite possible and expected with wireless/radio networks)
- A DODAG will ensure nodes always have a path up towards the root
- A DODAG is identified by {RPL Instance ID, DODAG ID}



Objective Function (OF)

- An OF defines how nodes select paths towards DODAG root
  - Dictates rules on how nodes satisfy a optimisation objective (e.g., minimise latency)
  - Based on routing metrics and constraints carried ICMPv6 control messages
- The OF computes a device rank relative to its distance from the DODAG root

Rank =

Objective Function Example	
Optimisation Objective	Routing Metrics
•Energy Minimisation •Latency •Other Constraints	•Link Metrics •Node Metrics

Rank is higher as distance increases from DODAG root

- Derived rank is advertised to other nodes
- OF decoupled from the routing protocol
- The RPL specification does not include OF definitions
  - OF related to specific applications defined in separate documents (RFCs)
- One Objective Function = One RPL Instance {One or more DODAGS}

Objective Code Points (OCP)

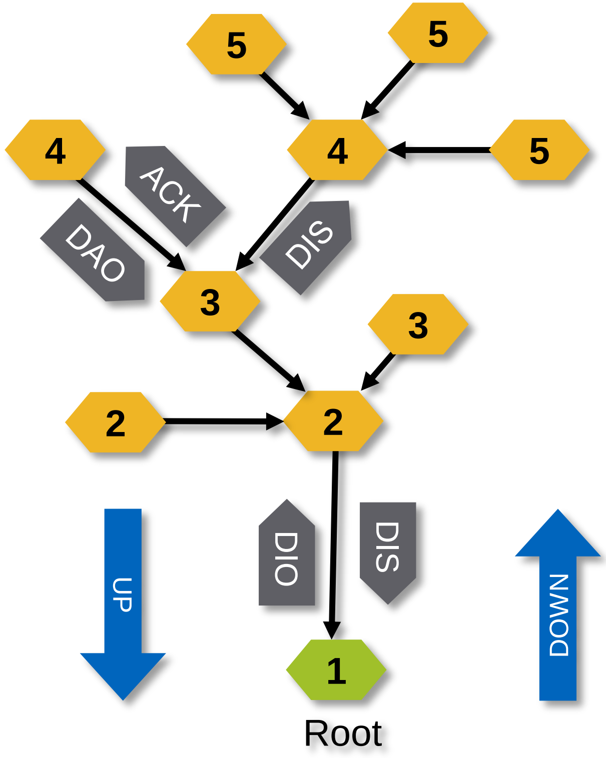
- The OCP indicates the method used to construct the DODAG to meet an OF
  - Defines how nodes should combine metrics and constraints consistently to derive a rank
  - The OCP is the implementation of an Objective Function
- RPL allows OCP to be very flexible in its methods and use of constraints

OCP Method	Example	DODAG Root
Fixed	Link Latency MUST be < 10 seconds	DODAG root cannot override latency constraint
Flexible	Link Latency SHOULD be < 10 seconds	DODAG root can advertise new latency constraint
General	Use link with best latency	DODAG root does not advertise any constraint
Defer	Link Latency should meet advertised constraint	DODAG root advertises actual constraint

- DODAG root can advertise constraints in ICMPv6 messages
- Objective Code Points are 16 bit values assigned by IANA
  - OCP0 defined as the default objective function RFC 6552

ICMPv6 RPL Control Messages

Message	Meaning	Function
DIO	DODAG Information Object	DODAG discovery, formation, maintenance
DIS	DODAG Information Solicitation	Probe neighbourhood for nearby DODAGs
DAO	Destination Advertisement Object	Propagates destination information up DODAG
DAO-ACK	DAO Acknowledgement	Unicast acknowledgement to a DAO message
CC	Consistency Check	Check secure message counters (for secure RPL)



- ICMPv6 message type 155 - RPL Control message
  - Each RPL control message has a secure variant (Refer Section 6.1 of RPL spec)
- Most RPL control messages have scope of a link
  - Exception is DAO/DAO-ACK in non-storing mode passes over multiple hops

Destination	Source	
Link Local FE80::/64	Link Local FE80::/64	RPL Control Payload
All RPL Nodes FF02::1A	Link Local FE80::/64	RPL Control Payload
Global/Unique Local 2000::/3 or FC00::/7	Global/Unique Local 2000::/3 or FC00::/7	DAO/DAO-ACK Payload (non-storing)

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Routing Metrics and Constraints in LLNs

Constraint	Provides a path filter for more suitable nodes and links
Metric	A quantitative value used to evaluate a path cost

- Concept of routing objects that can be treated as a metric or a constraint
  - Low pass thresholds used to avoid unnecessarily recomputing DAG
  - Metrics and constraints are advertised in DIO messages
- Computing dynamic metrics takes up power and can change rapidly
  - Solved by abstracting number of discrete values to a metric

Link Quality Metric Example	
Value	Meaning
0	Unknown
1	High
5	Medium
7	Low

Tradeoff

Reduced accuracy vs overhead and processing efficiency

- RFC 6551 Routing Metrics in LLNs

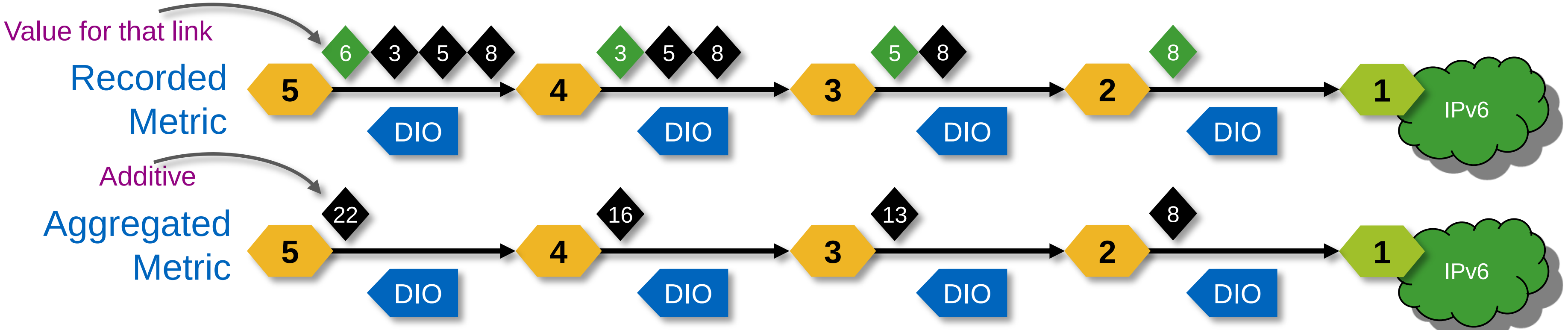
Current Routing Metric/Constraint Objects in LLNs

Node Object	Link Object
Node State and Attributes Object Purpose is to reflects node workload (CPU, Memory…) "O" flag signals overload of resource "A" flag signal node can act as traffic aggregator	**Throughput Object** Currently available throughput (Bytes per second) Throughput range supported
Node Energy Object "T" flag: Node type: 0 = Mains, 1 = Battery, 2 = Scavenger "I" bit: 0 = Exclude, 1 = Include (bits set in node type field) "E" flag: Estimated energy remaining flag "E-E" field contains estimated % energy remaining	**Latency** Can be used as a metric or constraint Constraint - max latency allowable on path Metric - additive metric updated along path
Hop Count Object Can be used as a metric or constraint Constraint - max number of hops that can be traversed Metric - total number of hops traversed	**Link Reliability** Link Quality Level Reliability (LQL) 0=Unknown, 1=Highest … …7=Lowest Expected Transmission Count (ETX) (Average number of TX to deliver a packet)
	Link Colour Metric or constraint, arbitrary admin value

Link and Node metrics are usually (but not necessarily) additive along a path to the DODAG root

Advertising Routing Metrics

- Node advertise node and link metrics in a DIO message metric container
- Metrics can be recorded or aggregated along the path up to the DODAG root

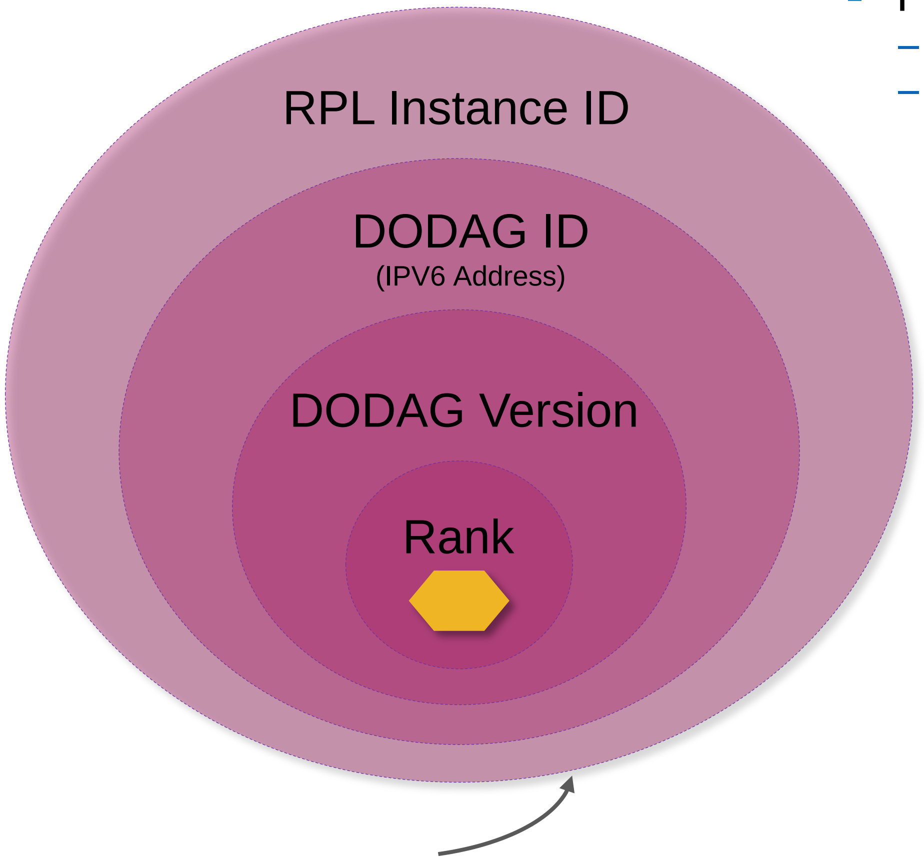


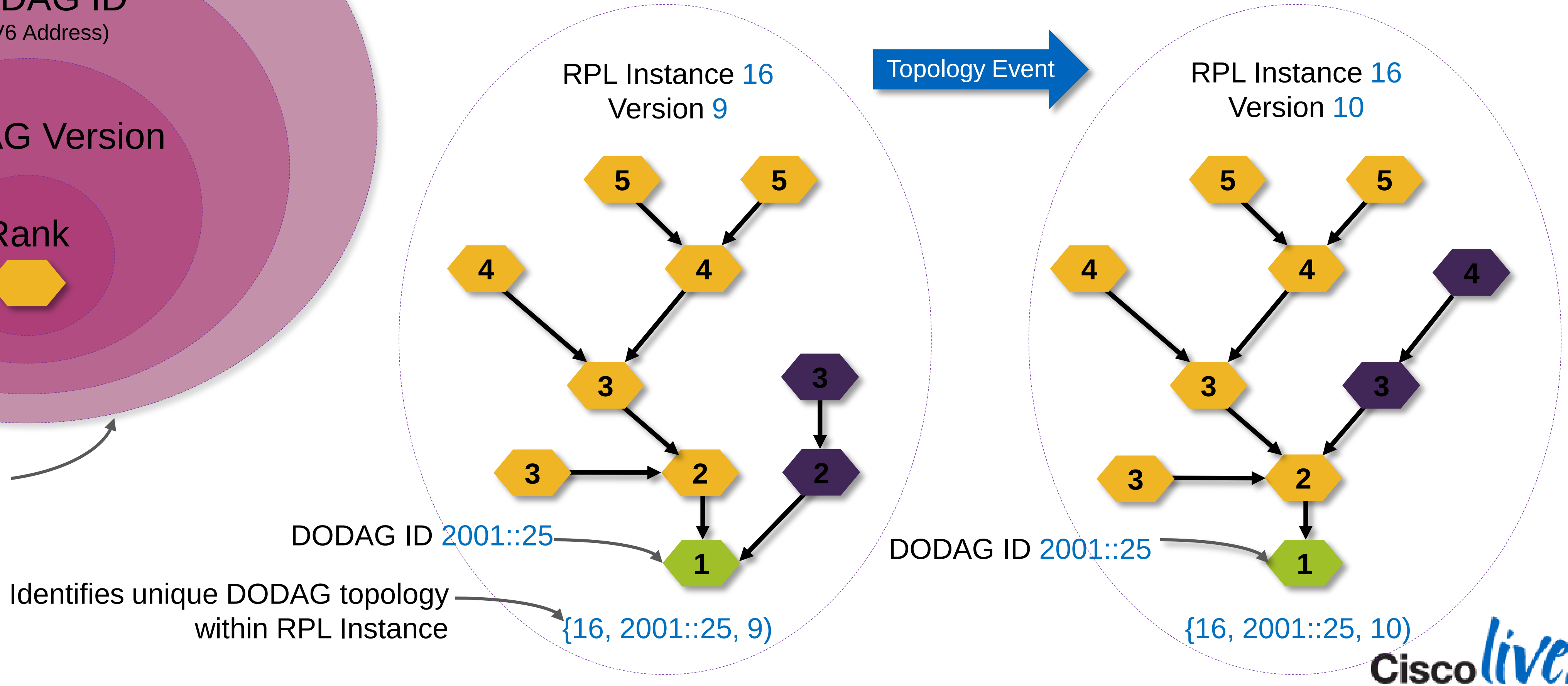
- An aggregated routing metric can be processed in several ways

Agg Type	Processing	Example at 5
0x00	The routing metric is additive	22
0x01	The routing metric reports a maximum	8
0x02	The routing metric reports a minimum	3
0x03	The routing metric is multiplicative	5760

RPL Identifiers

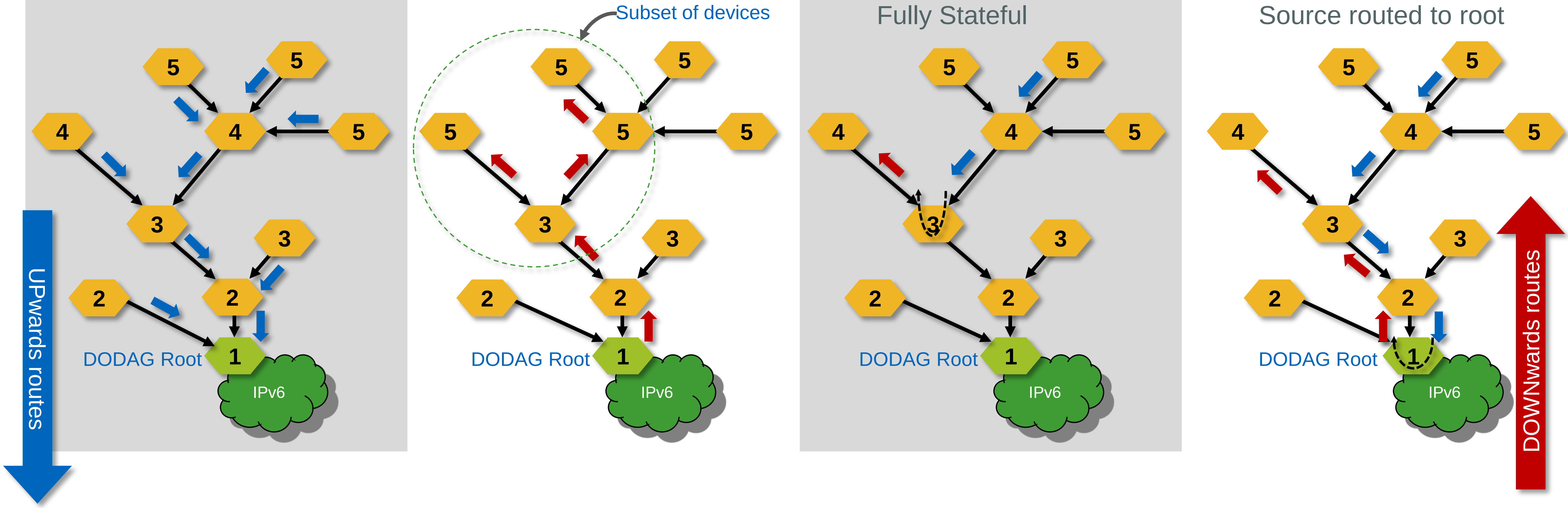
- Four values used to identify and maintain DODAG topology
  - Nodes in a particular topology will belong to the same DODAG version
  - Rank within {RPL Instance ID, DODAG ID, DODAG Version} scope





RPL Supported Traffic Flows

- Multipoint to Point
  - DIO messages
- Point to Multipoint
  DAO messages
- Point to Point
  Storing Mode, DAO
  Fully Stateful
- Point to Point
  Non-Storing Mode, DAO
  Source routed to root



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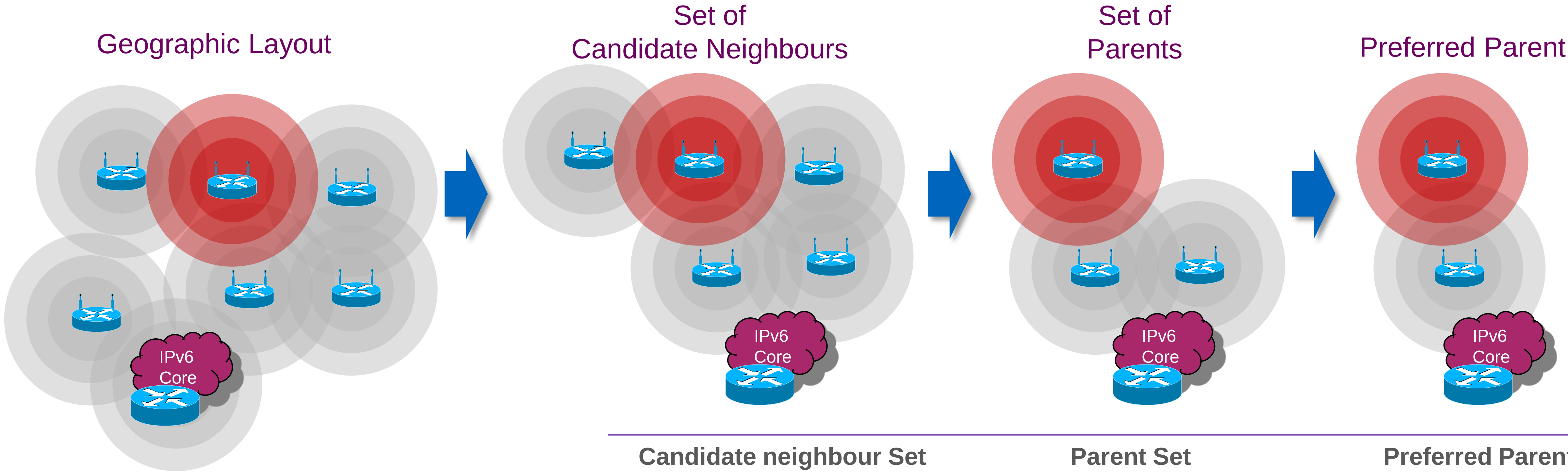
DODAG Neighbours and Parent Selection



- Upward route discovery
  - Comprises three logical sets of link-local nodes
  - Neighbours are learnt from DIO advertisements

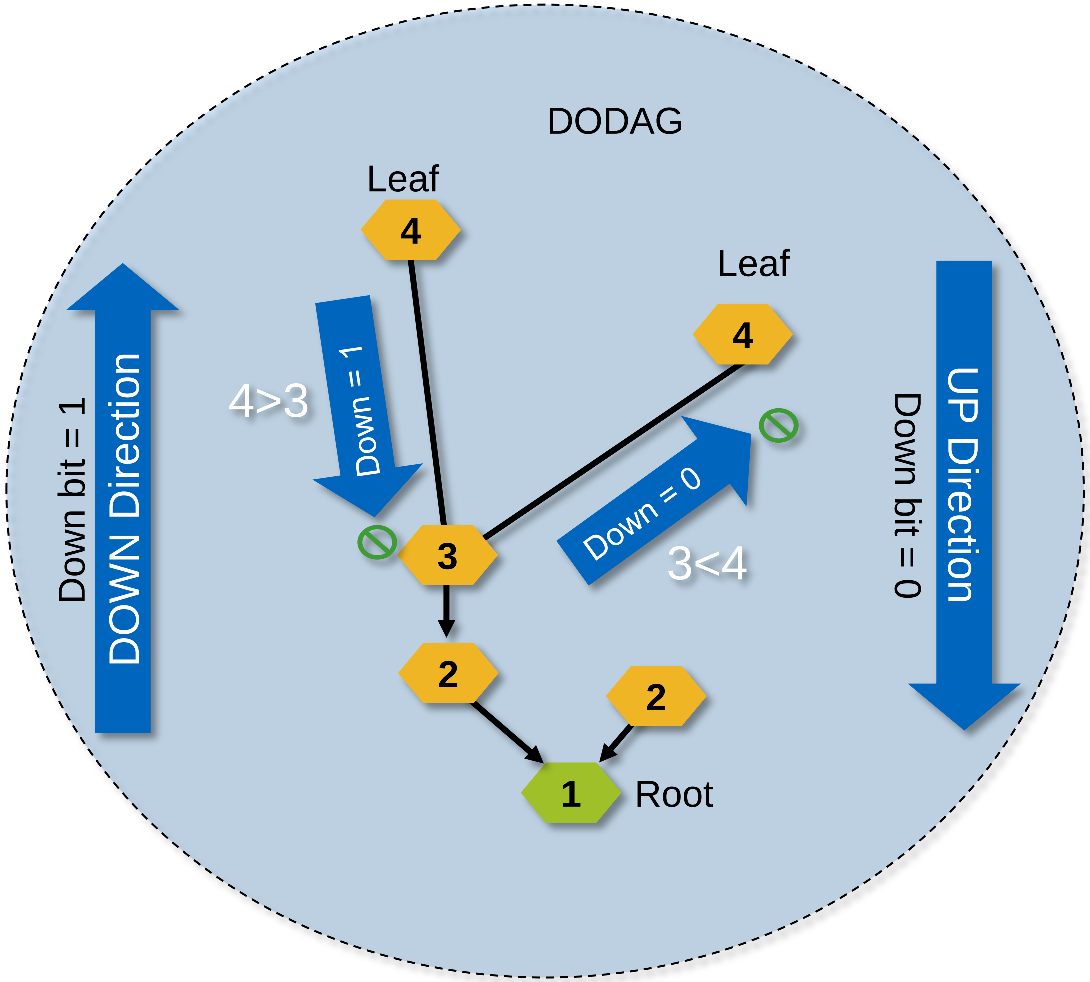
Candidate neighbour Set	Parent Set	Preferred Parent
Subset of nodes reachable via link-local multicast	Consists of nodes with a higher rank (lower #)	Preferred next-hop to the DODAG Root
Elements in the set MAY belong to different DODAG versions	Elements in the set MUST belong to SAME DODAG version	Multiple preferred parents possible if ranks are equal

RPL Security

- RPL supports optional message confidentiality and integrity
  - Link-layer mechanisms can be used instead when available
  - RPL security mechanisms can be used in the absence of link-layer
  - Refer to Section 10 of RPL standard
- RPL supports three security modes

Security Mode	Description
Unsecured	RPL message sent unsecured - may underlying security mechanisms
Pre-installed	RPL nodes use same pre-shared/installed key to generate secure RPL messages
Authenicated	Uses pre-installed key to allow RPL node to join as a leaf only To function as a router requires obtaining a key from authentication authority

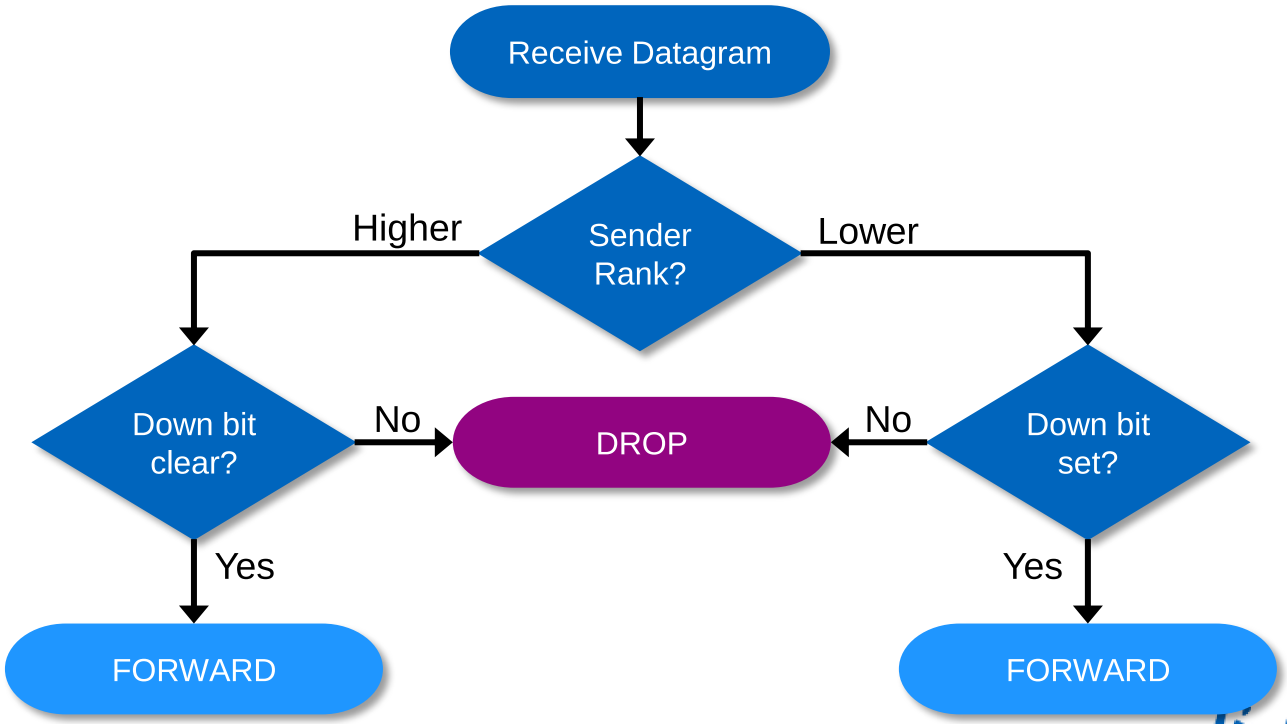
RPL Loop Detection



- Data path validation used to check for loops
- RPL Information carried in IPv6 options header
  - "Down bit" to signal datagram direction

    0 (Clear) := datagram path towards root (UP)

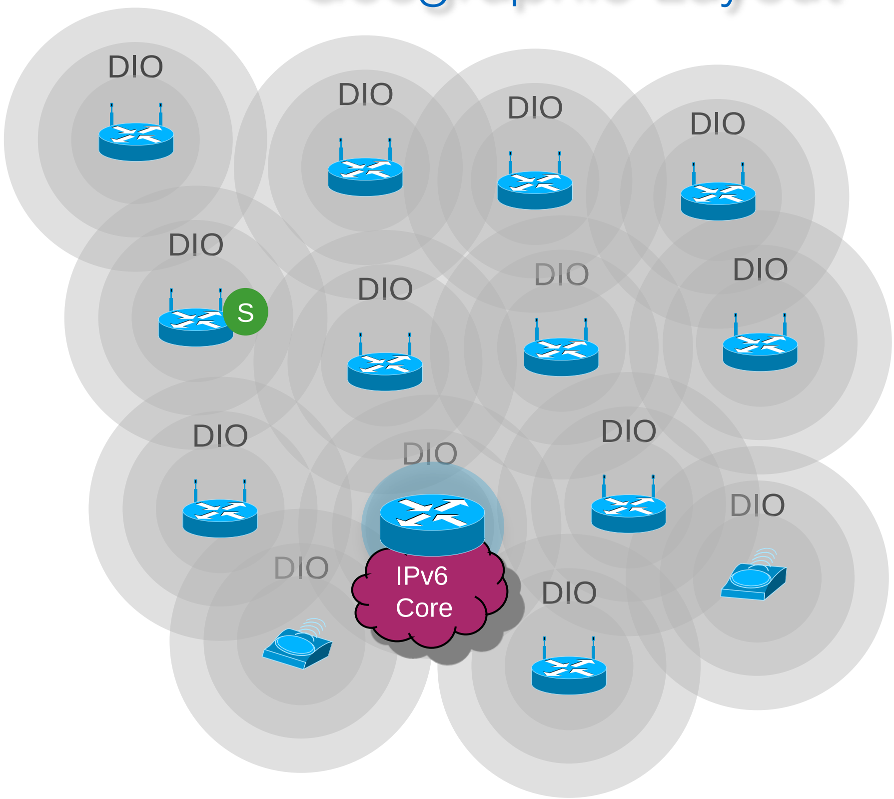
    1 (Set) := datagram path towards leaf (DOWN)
  - "Sender Rank" rank inside DODAG of sender



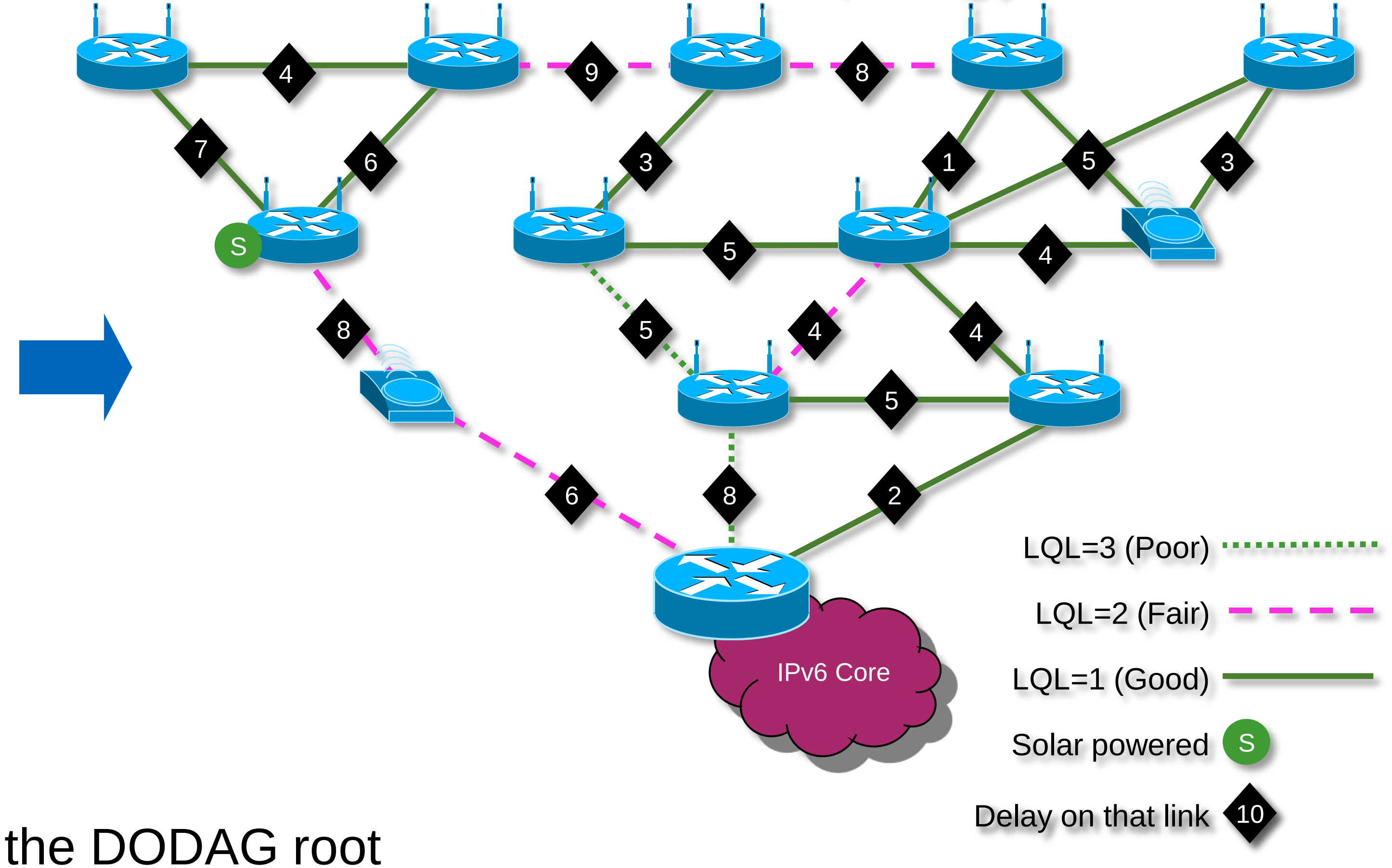
DODAG Examples

DODAG Examples

Geographic Layout



DODAG Topology

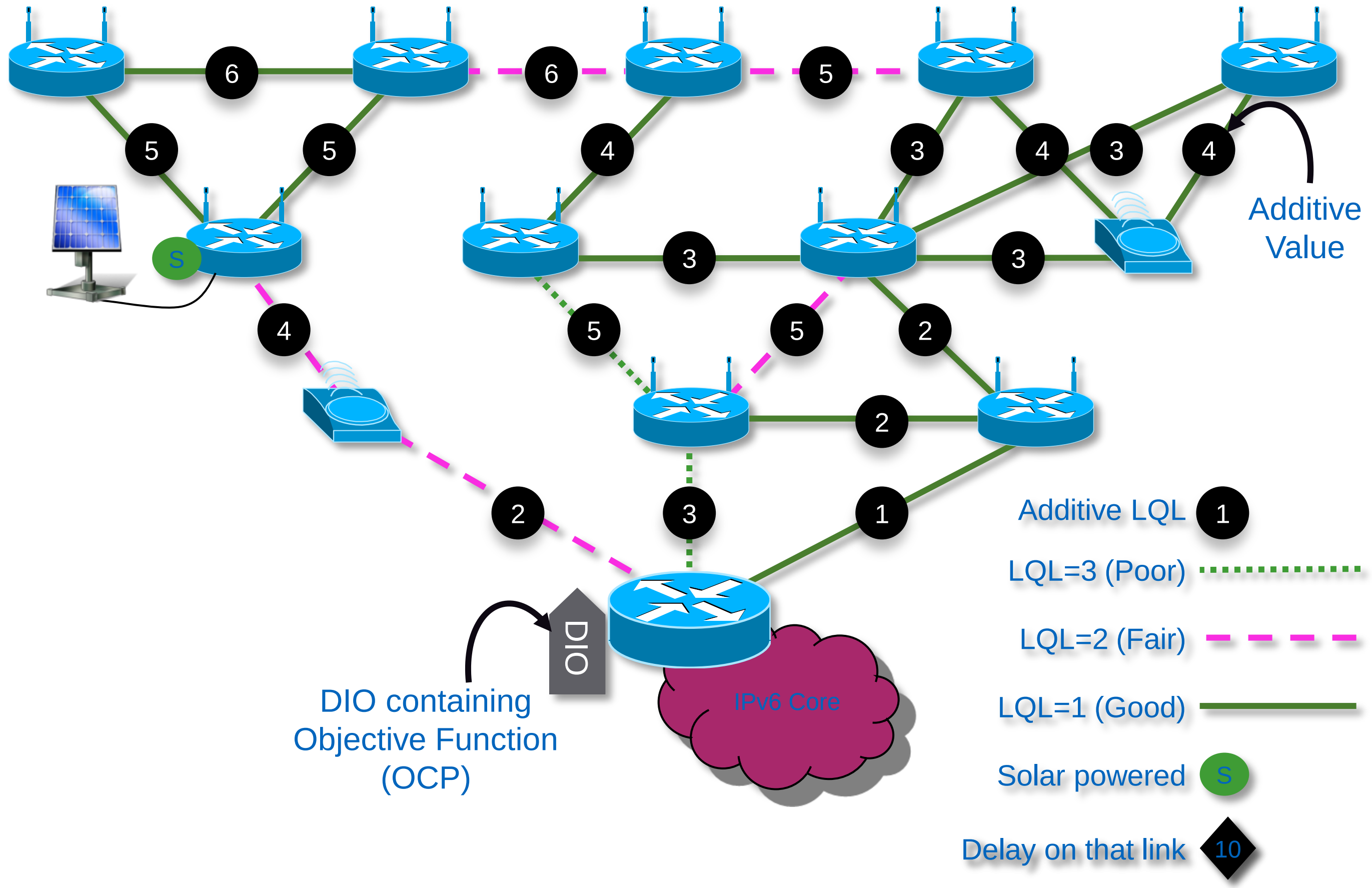


- DIO messages are propagated from the DODAG root
- Can carry OCP, metrics (recorded or aggregated), constraints

Objective Function #1 - Candidate Neighbours

Avoid Solar Powered Nodes and Use the Best Available Links (Additive) to get to the DODAG root

DODAG Topology



Objective Function

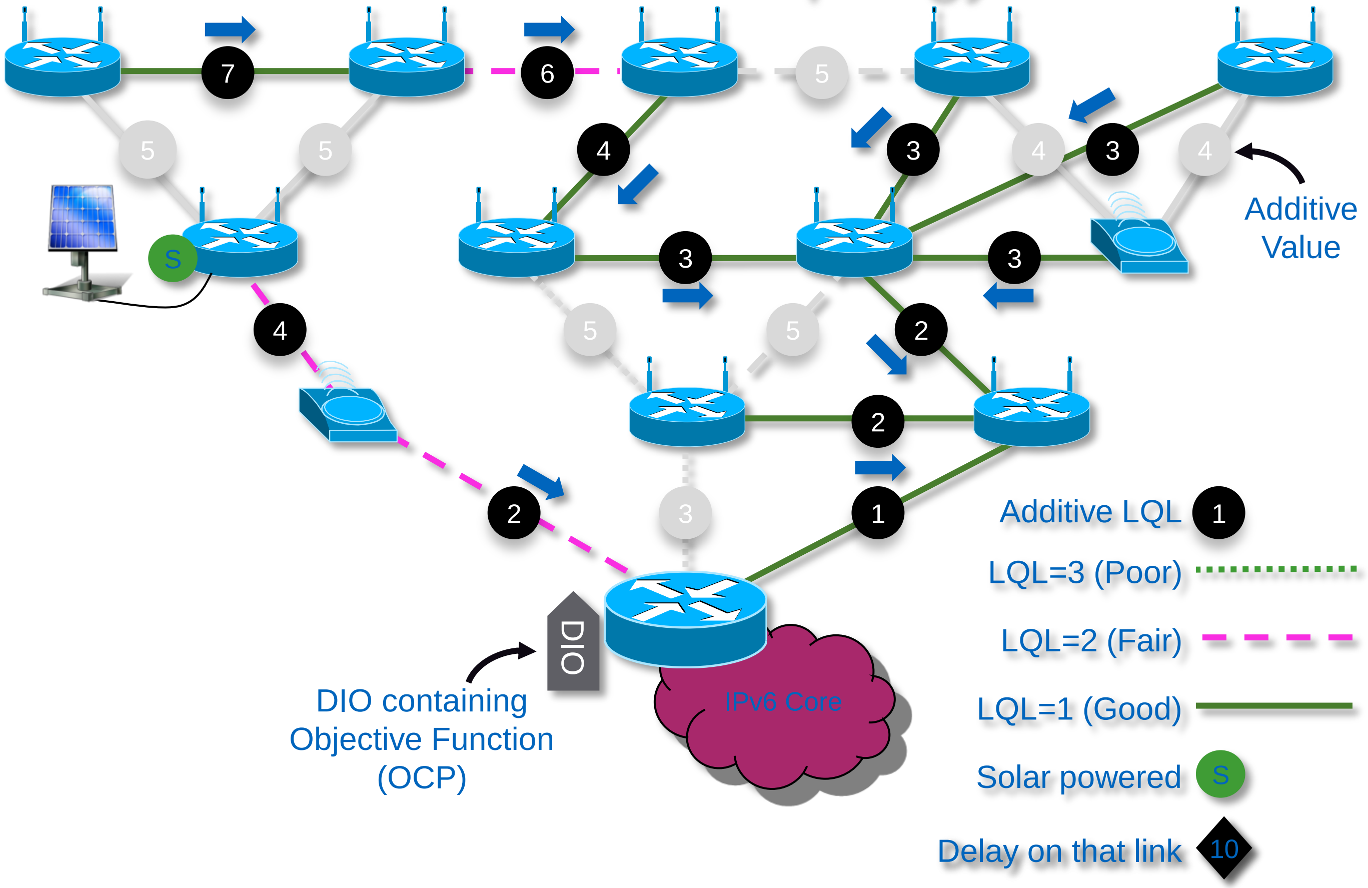
Object	Constraint	Advertised
Node Energy	Exclude Scavenger	As per OCP
Link Quality	Best Available (additive)	As per OCP
Hop Count	Maximum 20	Explicitly configured on DODAG root

- LQL metric advertised as additive
- Nodes choose links with lower LQL total

Objective Function #1 - Preferred Parents

Avoid Solar Powered Nodes and Use the Best Available Links (Additive) to get to the DODAG Root

DODAG Topology



Objective Function

Object	Constraint	Advertised
Node Energy	Exclude Scavenger	As per OCP
Link Quality	Best Available (additive)	As per OCP
Hop Count	Maximum 20	Explicitly configured on DODAG root

- LQL metric advertised as additive
- Nodes choose links with lower LQL total

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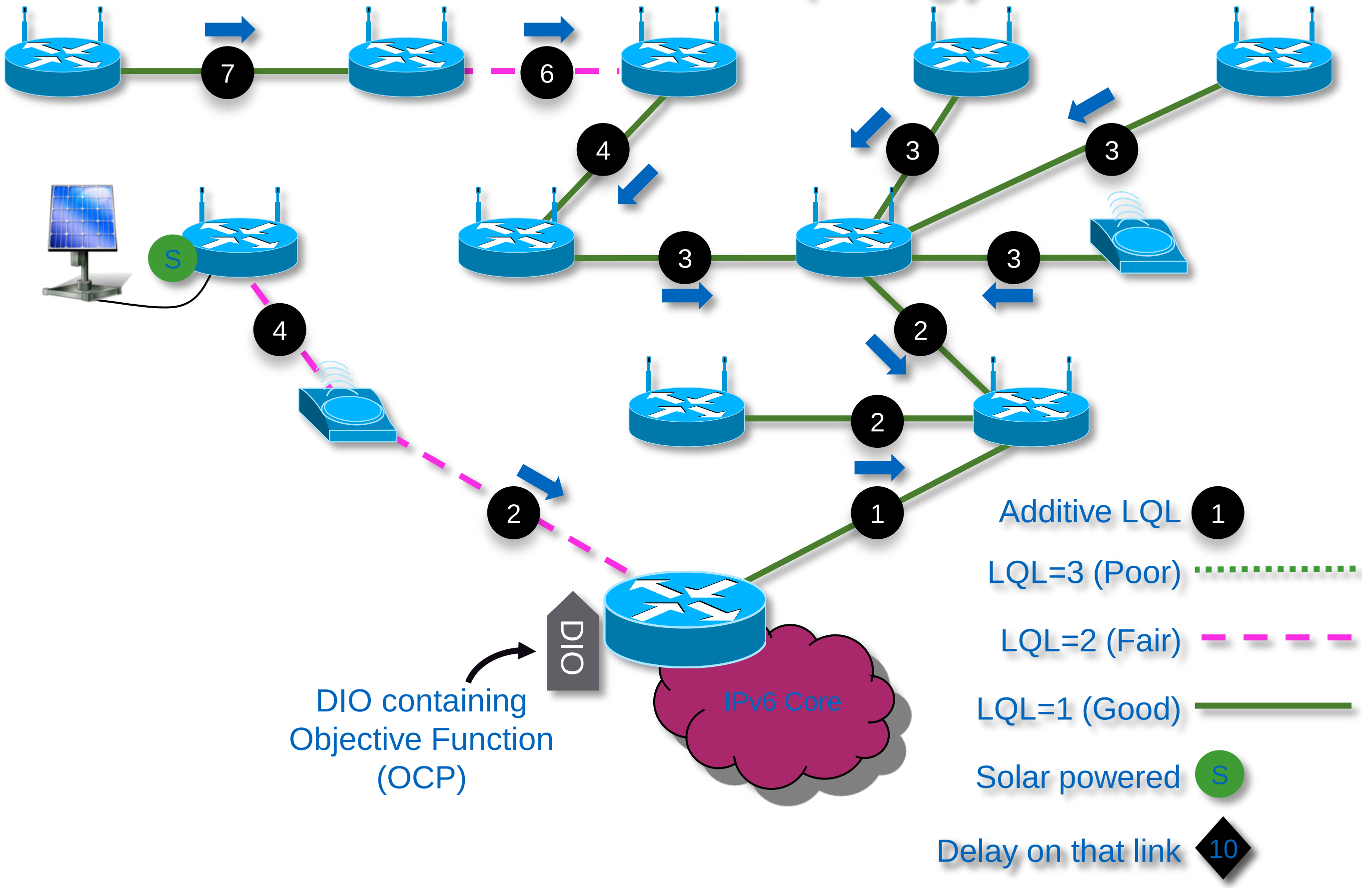
Objective Function #1 - Resulting DODAG

Avoid Solar Powered Nodes and Use the Best Available Links (Additive) to get to the DODAG Root

DODAG Topology



Objective Function

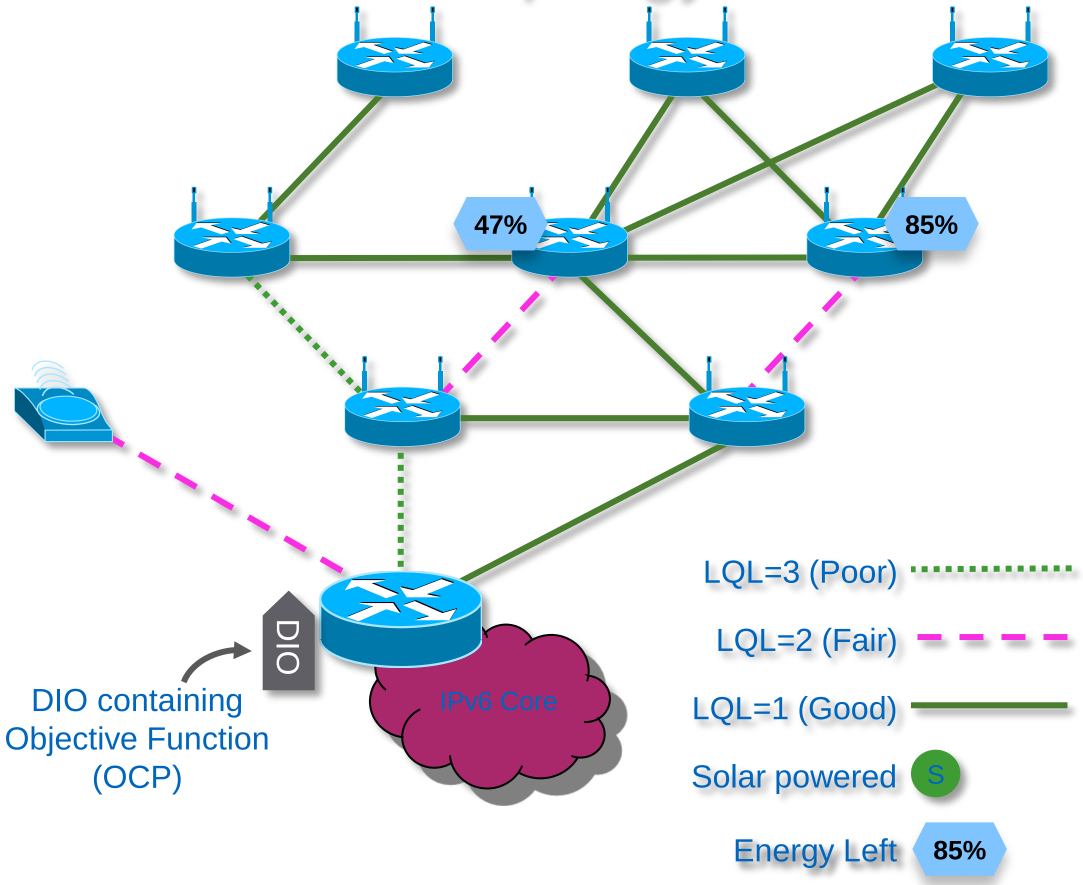
Object	Constraint	Advertised
Node Energy	Exclude Scavenger	As per OCP
Link Quality	Best Available (additive)	As per OCP
Hop Count	Maximum 20	Explicitly configured on DODAG root

- LQL metric advertised as additive
- Nodes choose links with lower LQL total

Objective Function #2 - Candidate Neighbours

Use Shortest Number of Hops and Avoid Low Energy Nodes

DODAG Topology



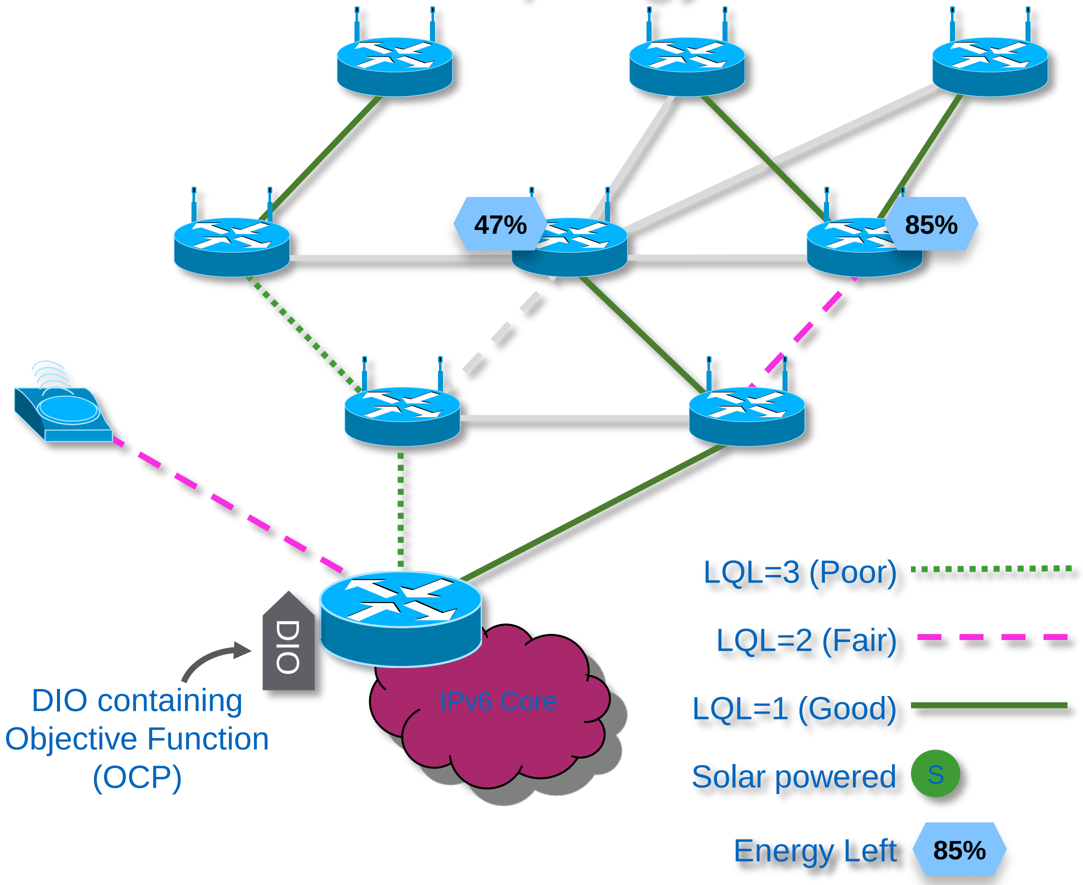
Objective Function

Object	Constraint	Advertised
Hops	Minimum Hops	As per OCP
Energy	Avoids nodes in path with < 50% energy	As configured on DODAG root

Objective Function #2 - Preferred Parents

Use Shortest Number of Hops and Avoid Low Energy Nodes

DODAG Topology



Objective Function

Object	Constraint	Advertised
Hops	Minimum Hops	As per OCP
Energy	Avoids nodes in path with < 50% energy	As configured on DODAG root

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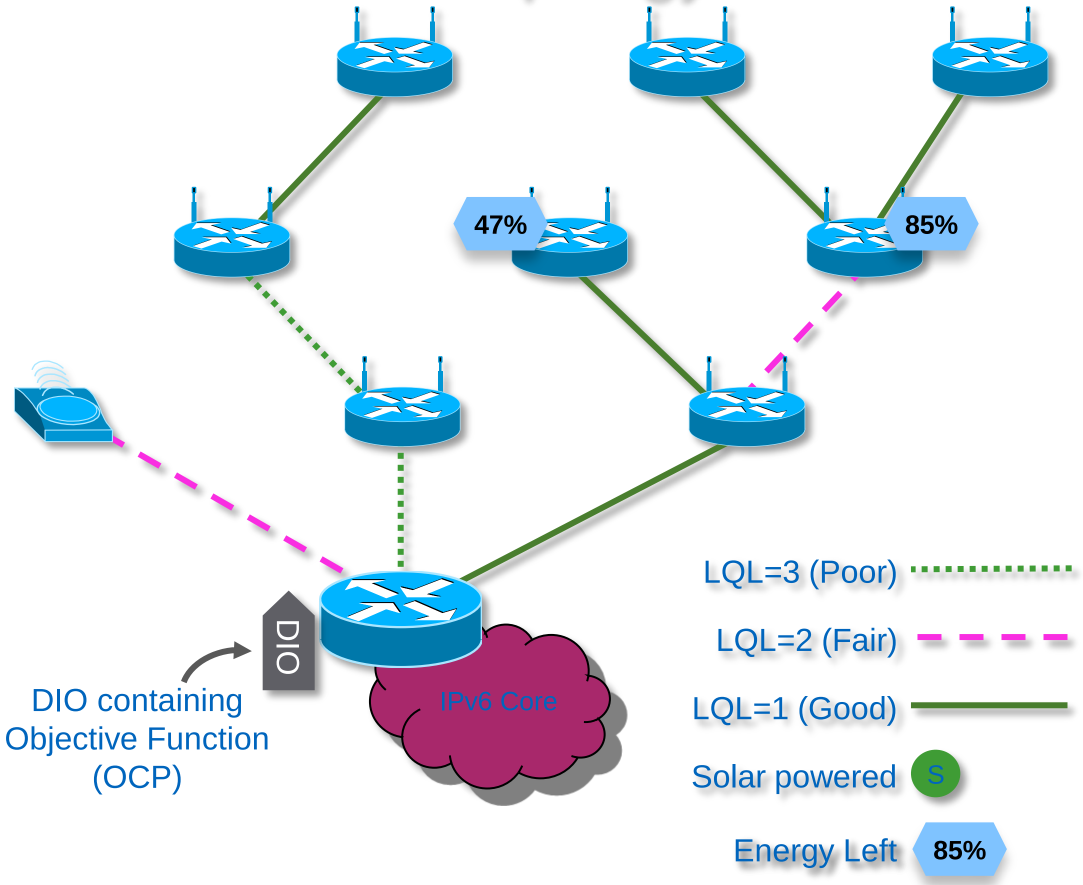
Objective Function #2 - Resulting DODAG

Use Shortest Number of Hops and Avoid Low Energy Nodes

DODAG Topology

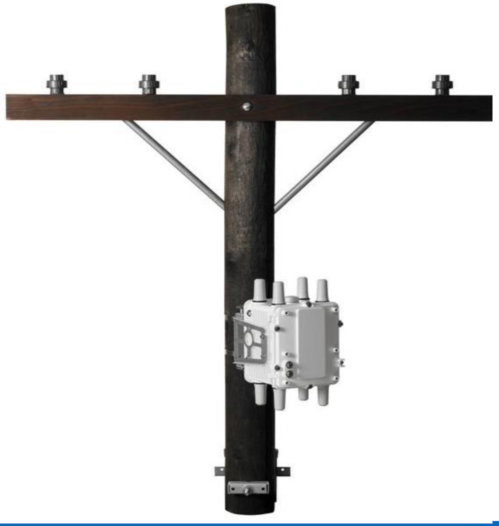


Objective Function

Object	Constraint	Advertised
Hops	Minimum Hops	As per OCP
Energy	Avoids nodes in path with < 50% energy	As configured on DODAG root

RPL Summary

- RPL is a foundation of the Internet of Things
  - Open standard to meeting challenging requirements
- Promising technology to enable IP on many billions of smart objects
- Very compact code
  - Supports wide range of media and devices
- Cisco Implementation
  - Incorporated into Cisco Grid Blocks Architecture
  - Available on Cisco CGR1000 series routers (indoor and poletop outdoor)



RPL Use Case

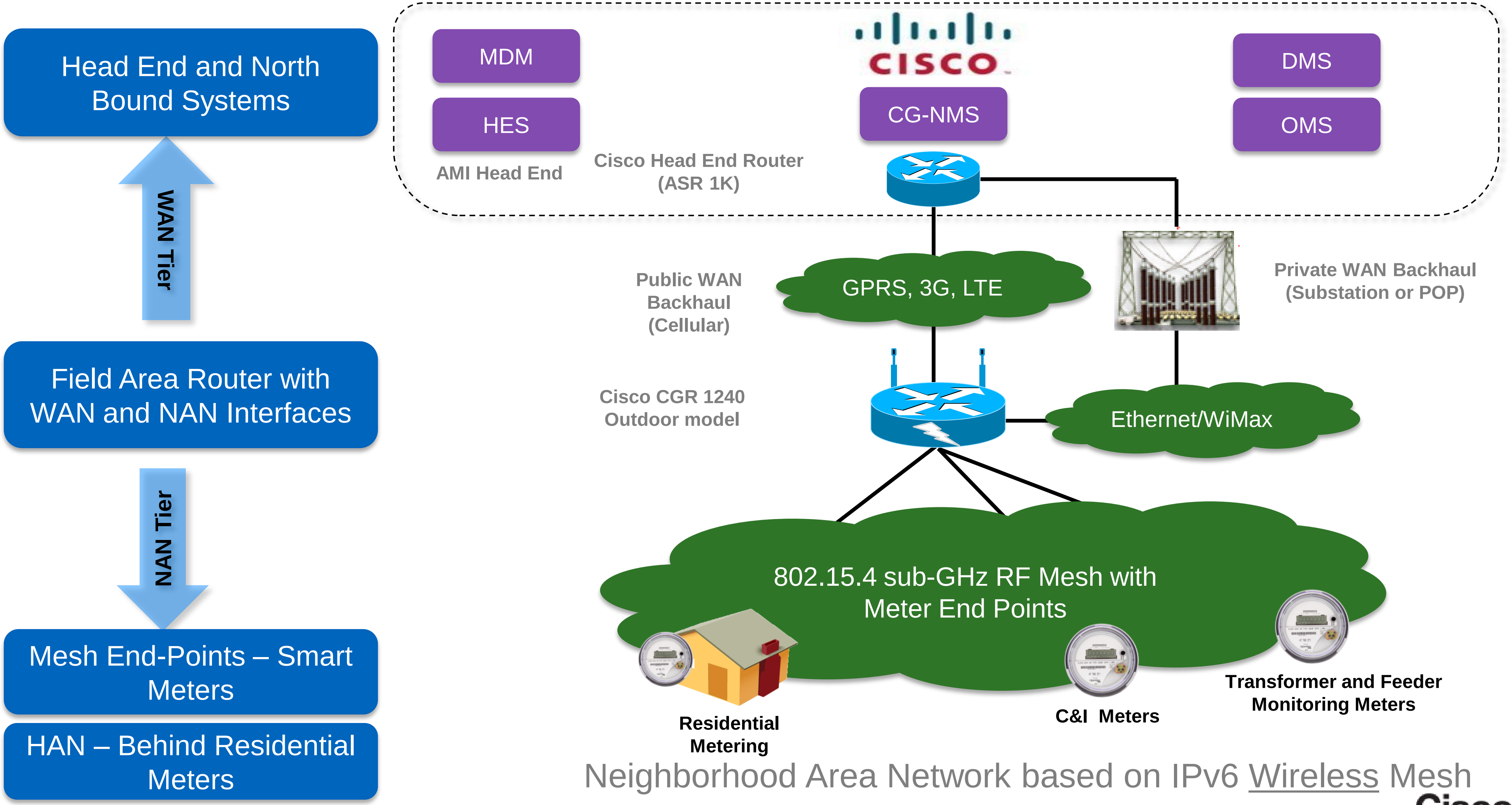
802.15.4g/e RF Mesh

Advanced Metering Infrastructure (AMI)

Advanced Metering Infrastructure

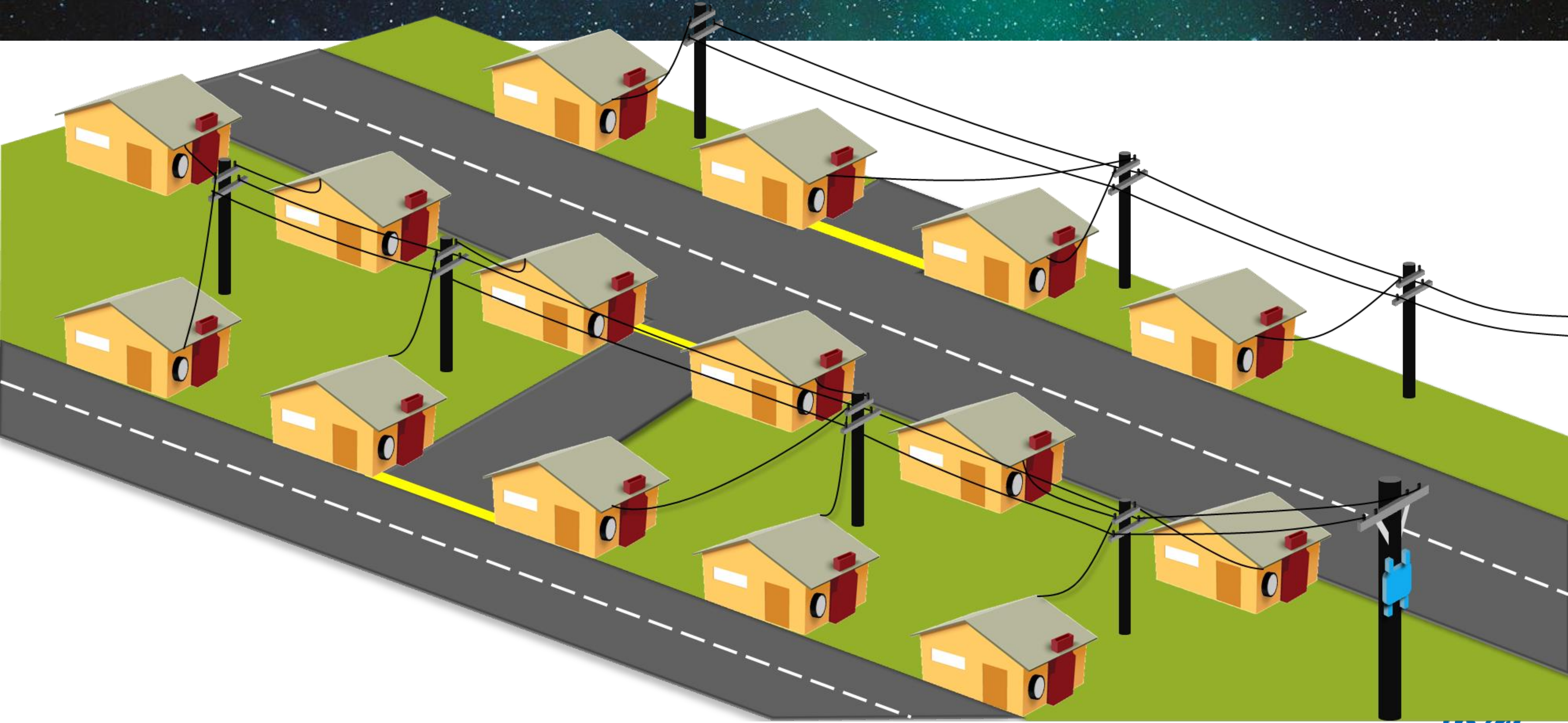
- Network solution to provide bi-directional power meter communications
- Part of Field Area Network (FAN) solution
  - Neighbourhood Area Network (NAN) - RPL Domain consisting of meters and possibly other smart objects
  - Wide Area Network (WAN) - Provides backhaul to management, billing, control systems
- NAN mesh network can be provided by RF (e.g., 802.15.4g) or PLC technologies
- Solution includes 3 main components:
  - Smart meters with embedded RF communications module (NAN) running Cisco Connected Grid Endpoint
  - Field Area Routers – CGR 1000 series – with NAN and WAN backhaul interfaces
  - Head End system - securely collect and manage meter data FCAPS management of comms network
- Cisco Systems and ITRON partnership
  - Cisco - provides the networking infrastructure, NMS, meter comms firmware (CG-Mesh) , outdoor routers
  - ITRON - provides the meter hardware (incl comms), reporting and collection systems (Openway)

AMI IEEE 802.15.4g RF Mesh Architecture

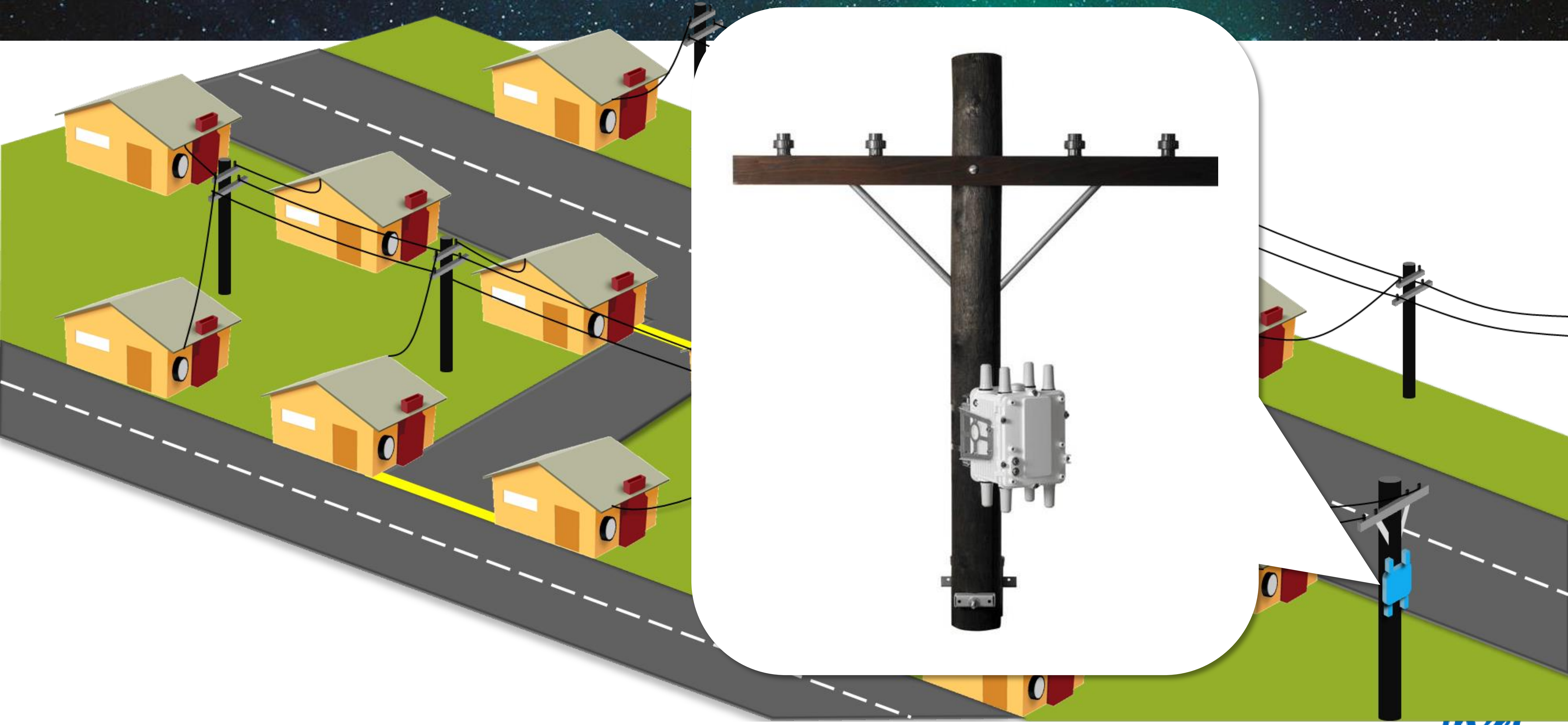


Neighborhood Area Network based on IPv6 Wireless Mesh

Advanced Metering NAN Urban Environment



DODAG Root - Cisco CGR 1240 (Field Area Router)



DODAG Root - Cisco CGR 1240 (Field Area Router)

IEEE 802.15.4g (902-928 Mhz)
IETF 6LowPan, IPv6, RPL
IEEE802.1ar device identity

3G GSM HSPA+, 3G CDMA 1xEV-DO
IEEE 802.16e (WiMAX)

WiFi, GigEthernet , FastEthernet
GPS

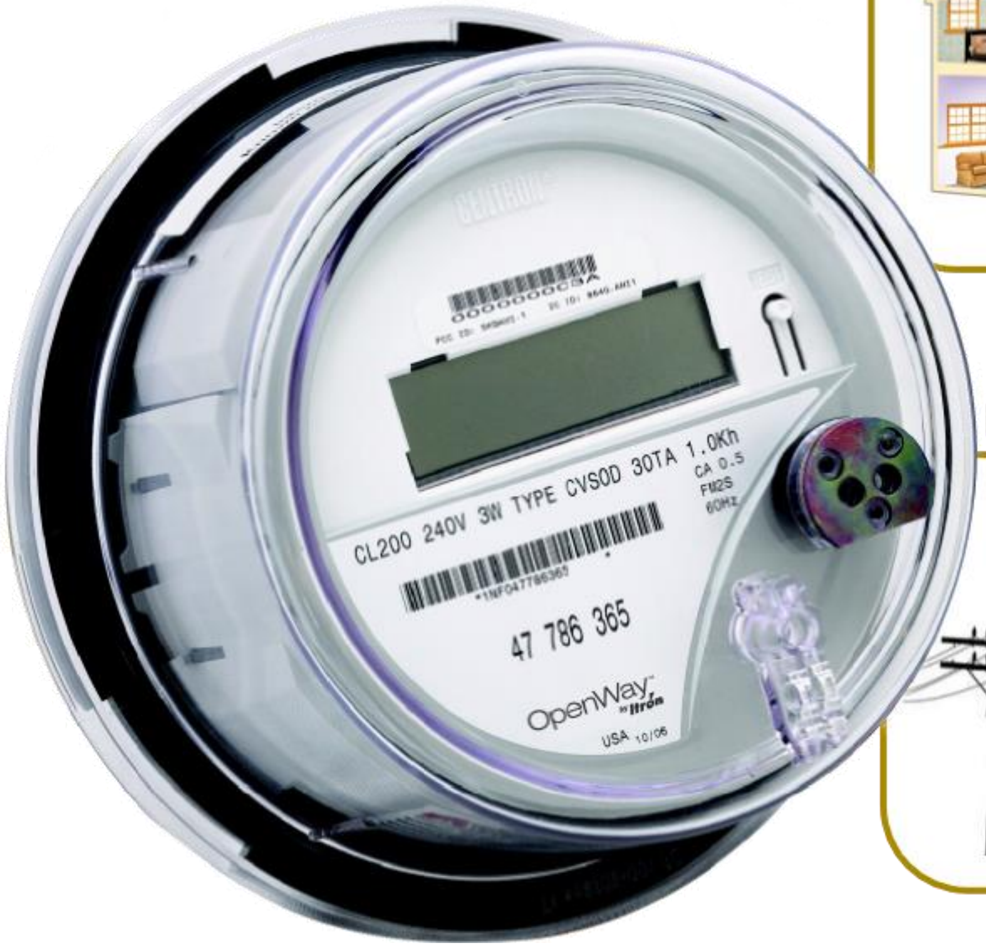
CGR1000 supports up to 5000 RPL nodes
(Currently tested with over 3600)

Outdoor/Pole Top version
CGR 1120 is the indoor version

ITRON Smart Meter with Embedded Cisco Firmware

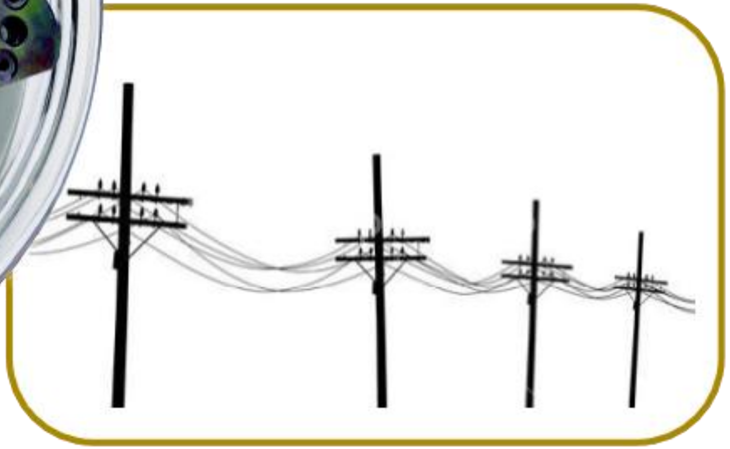
- Embedded Cisco CG-Mesh firmware in COMM module (RF unit, CPU…)
- IEEE 802.15.4g + AES 128 bit encryption
  IEEE 802.1x authentication
- IETF 6LowPan, IPv6, RPL
- No CLI access
  Only CSMP (CoAP management) using CISCO CG-NMS

ITRON Dual Antenna

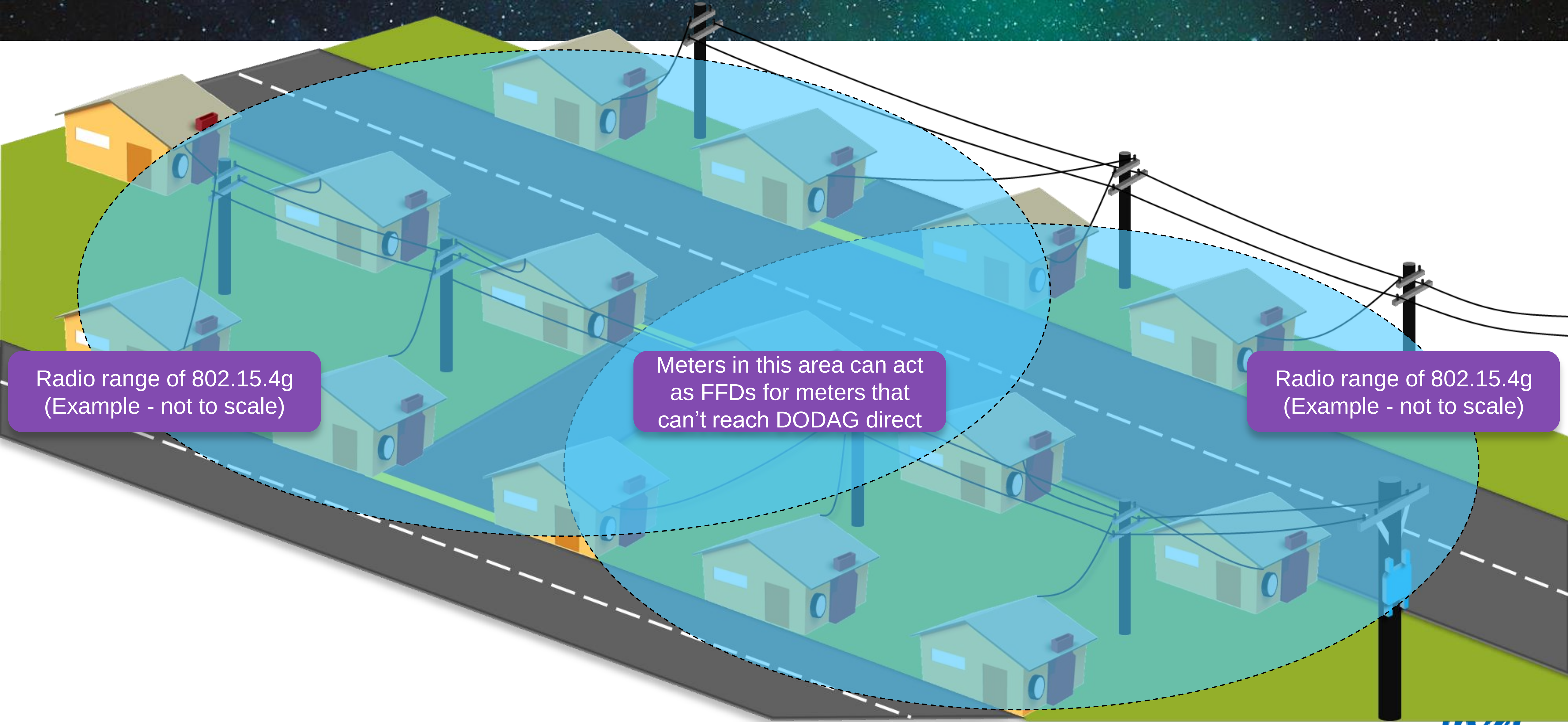


Home Area Network

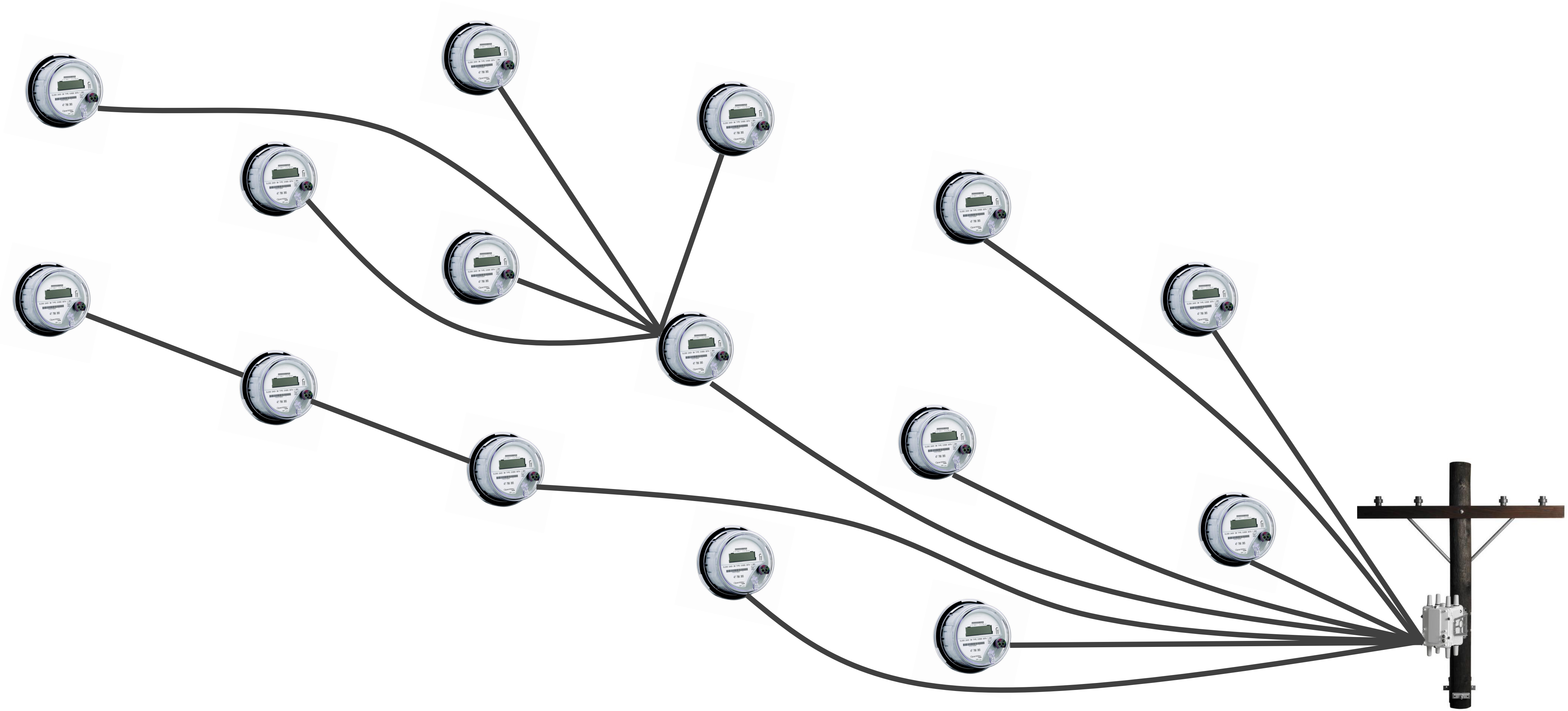
Neighbourhood Area Network



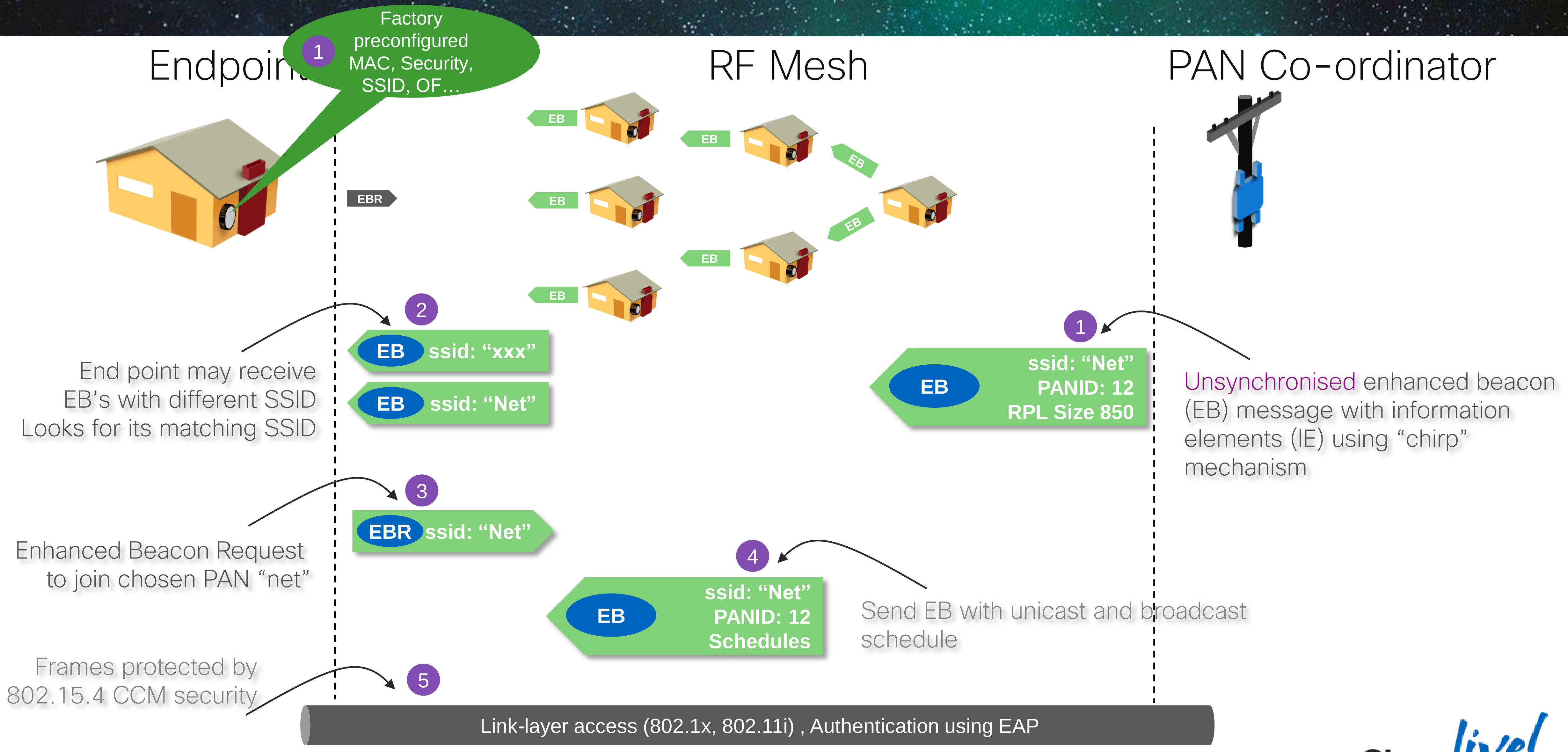
Smart Meters Can Be Used As Forwarders (FFDs)



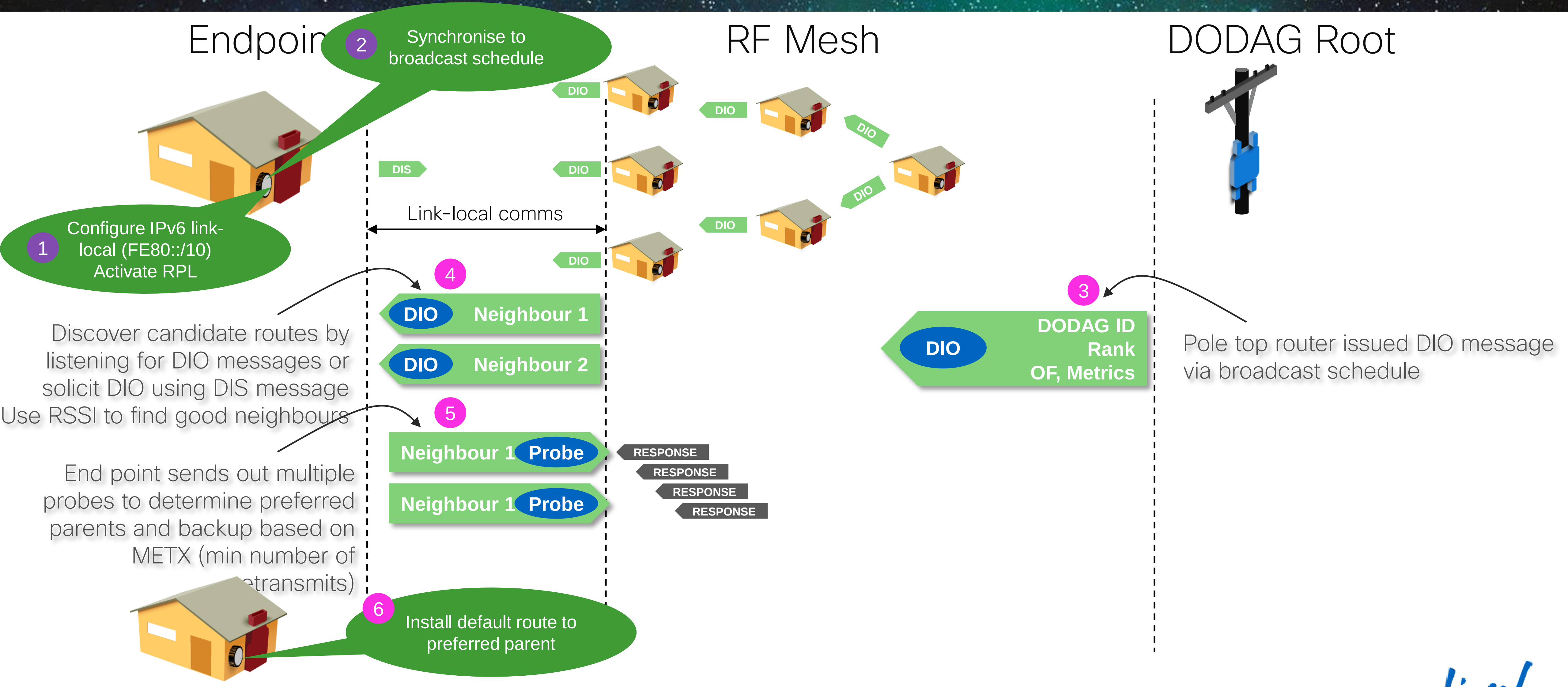
Possible Resulting DODAG Topology OF: Min ETX



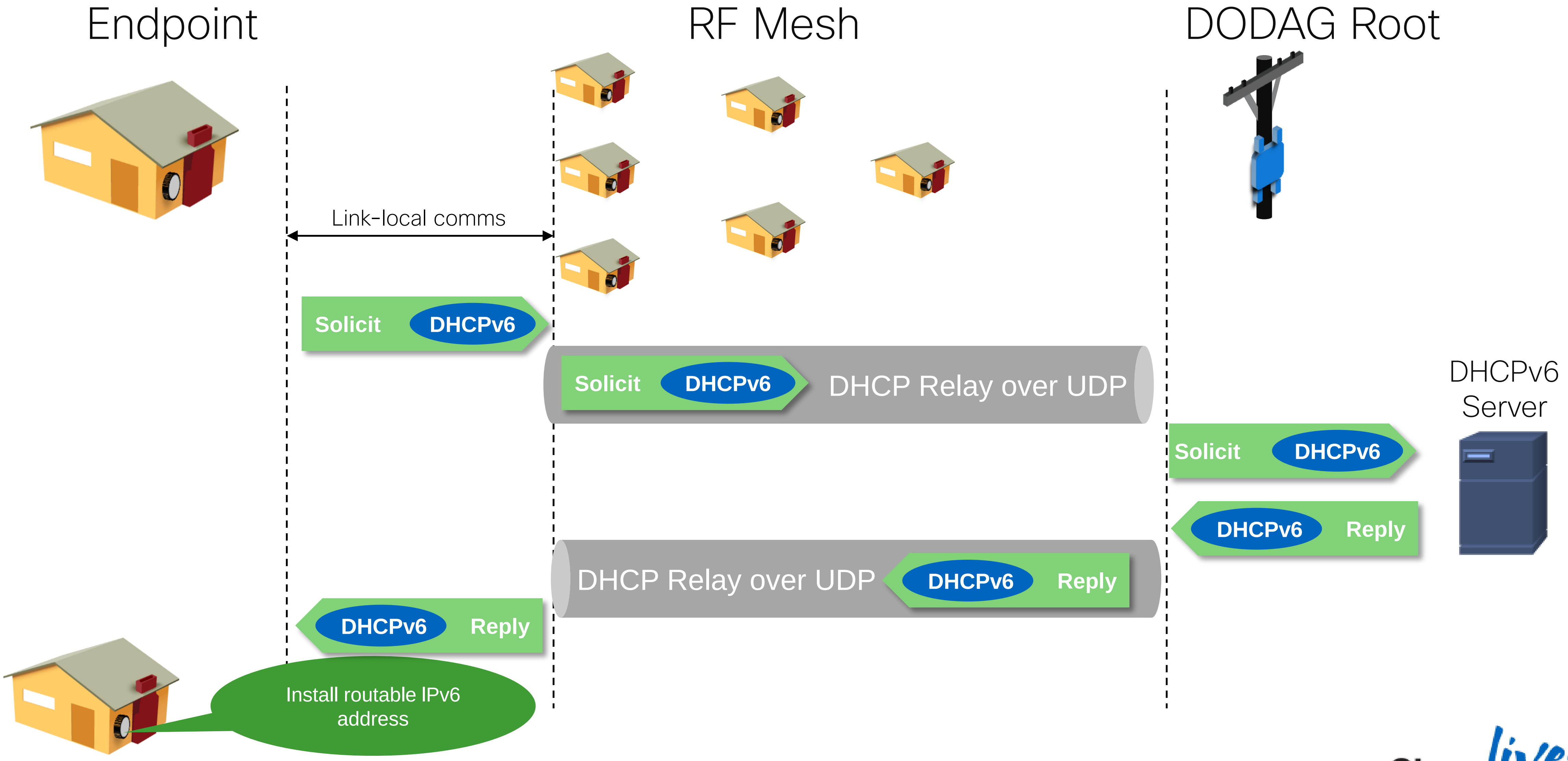
Network Discovery (Enhanced Beacon)



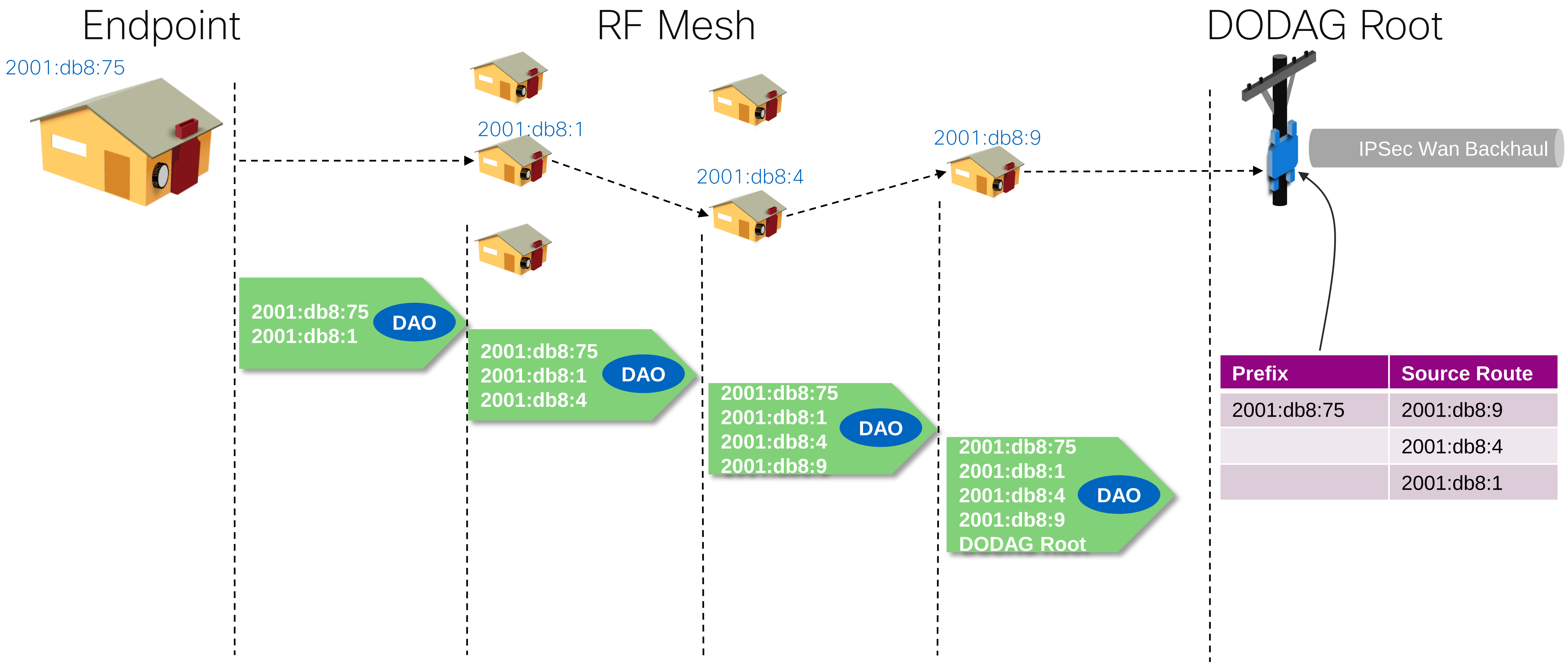
RPL Route Discovery (DIO Message)



IPv6 Address Allocation (DHCP)

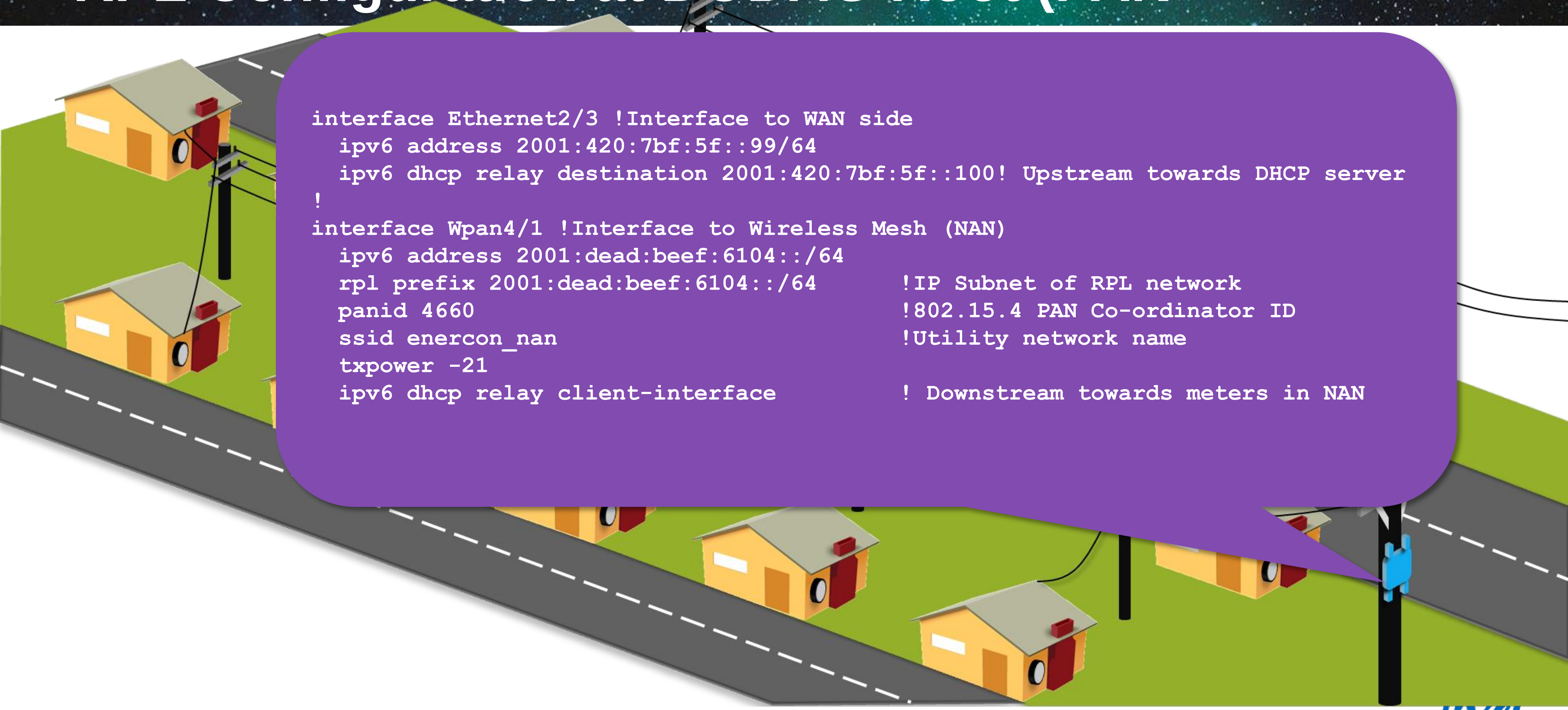


RPL Route Registration (DAO Message)

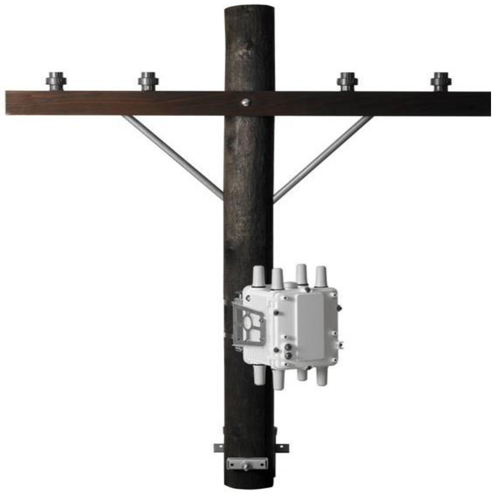


Prefix	Source Route
2001:db8:75	2001:db8:9
	2001:db8:4
	2001:db8:1

RPL Configuration at DODAG Root (FAN



```
interface Ethernet2/3 !Interface to WAN side
  ipv6 address 2001:420:7bf:5f::99/64
  ipv6 dhcp relay destination 2001:420:7bf:5f::100! Upstream towards DHCP server
!
interface Wpan4/1 !Interface to Wireless Mesh (NAN)
  ipv6 address 2001:dead:beef:6104::/64
  rpl prefix 2001:dead:beef:6104::/64      !IP Subnet of RPL network
  panid 4660                               !802.15.4 PAN Co-ordinator ID
  ssid enercon_nan                         !Utility network name
  txpower -21
  ipv6 dhcp relay client-interface         ! Downstream towards meters in NAN
```



RPL AMI Field Trial

IEEE 1901.2 NB-PLC

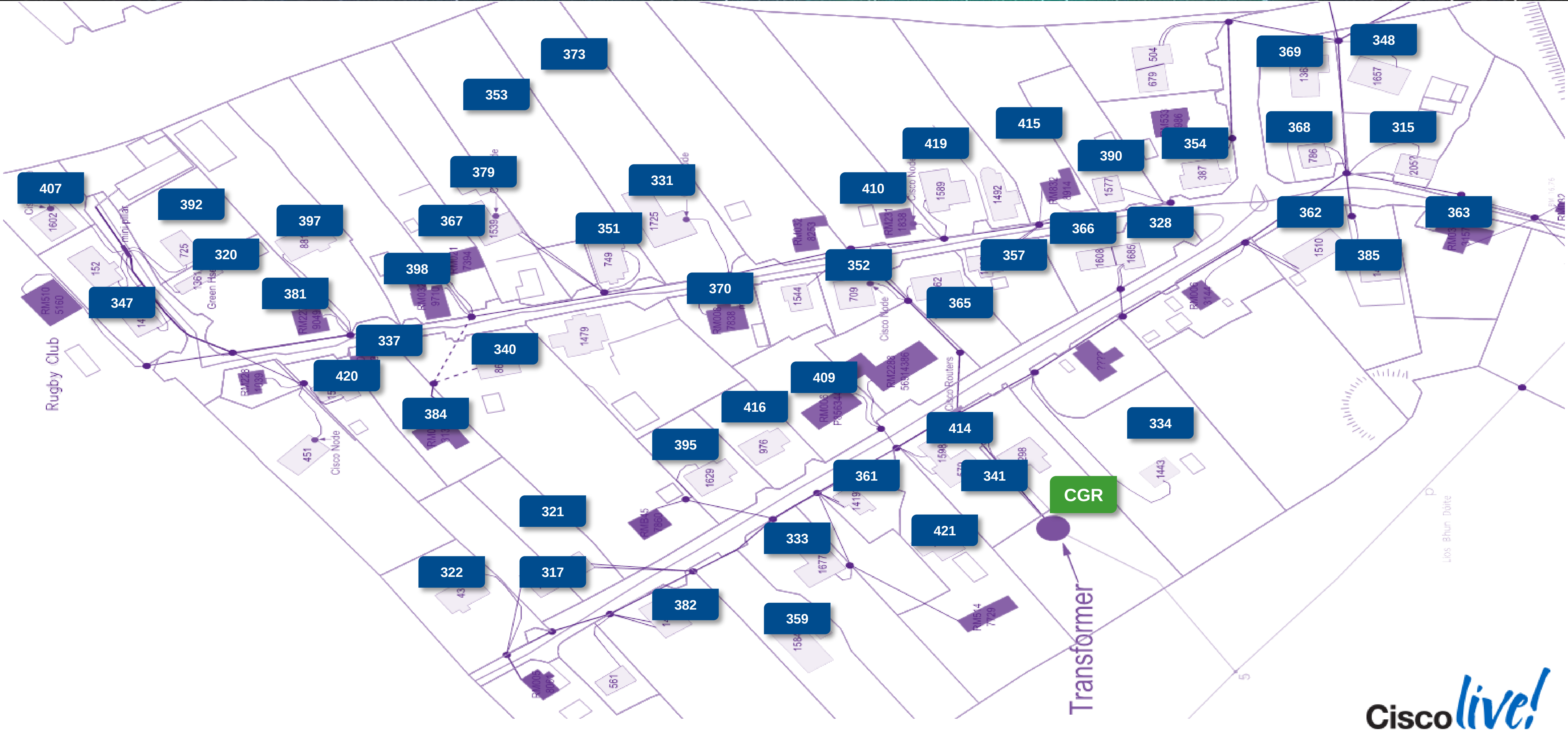
Field Test Location

- Location selected by the utility for its mix of power lines type
  - Aerial bundled cables
  - Aerial unbundled cables
  - Underground cables

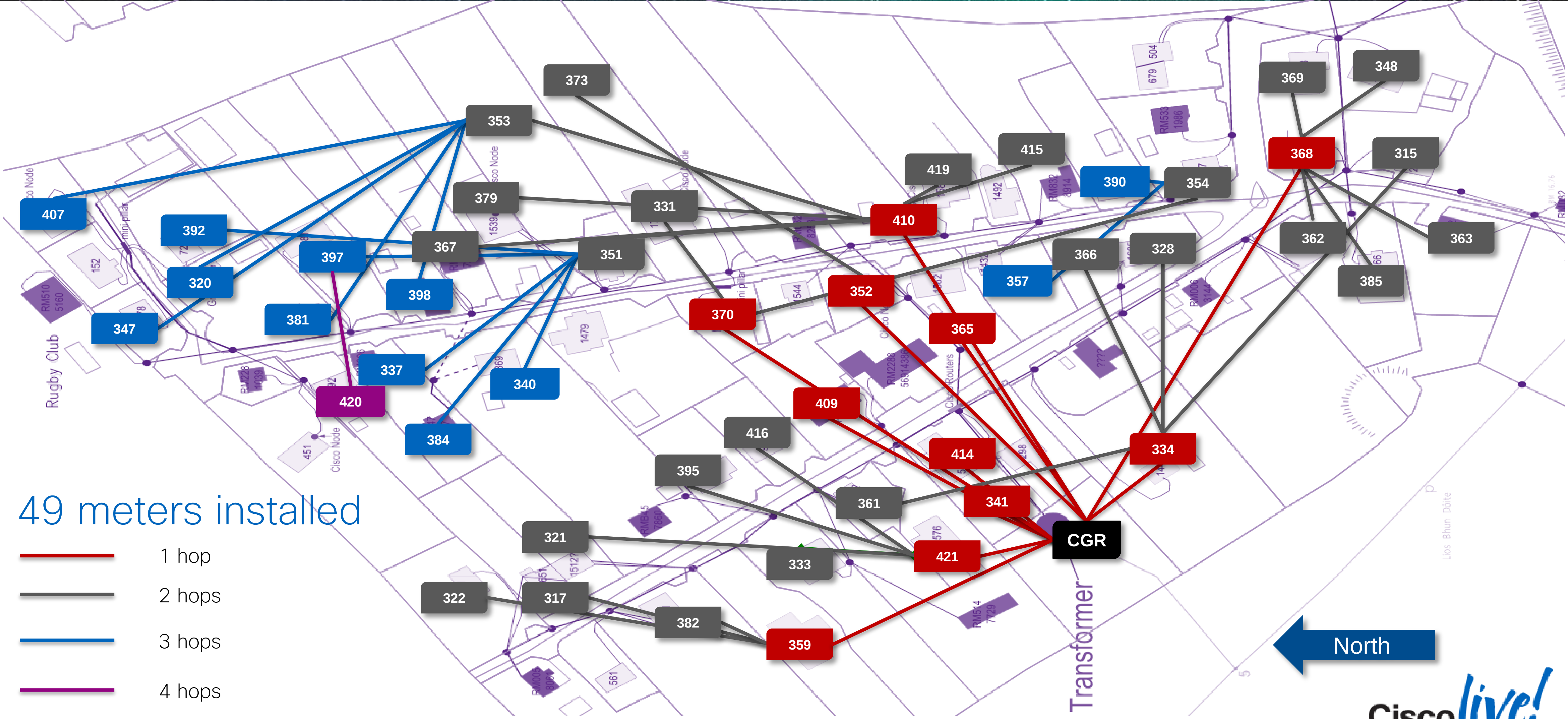
PLC Devices

- 1 x CGR 1120 with 3G and IEEE 1901.2 PLC interfaces
  - In a cabinet, pole mounted, 3 Phases PLC module, CG-OS 5.2(1)CG5(1)
- 48 x Itron IEC Centron meters with IEEE 1901.2 PLC running Cisco IPv6 SDK

Meter Deployment



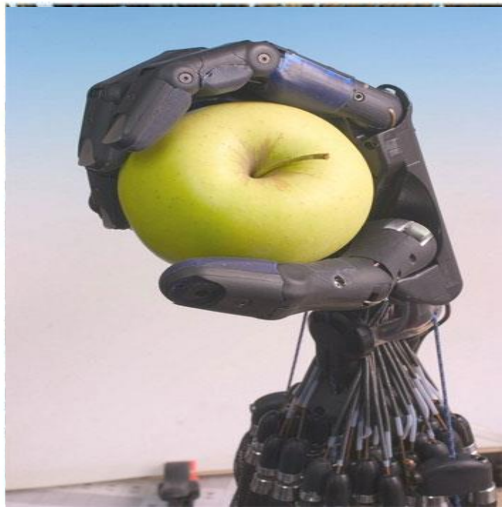
Resulting RPL Tree via IEEE 1901.2 NB-PLC



49 meters installed

- 1 hop
- 2 hops
- 3 hops
- 4 hops



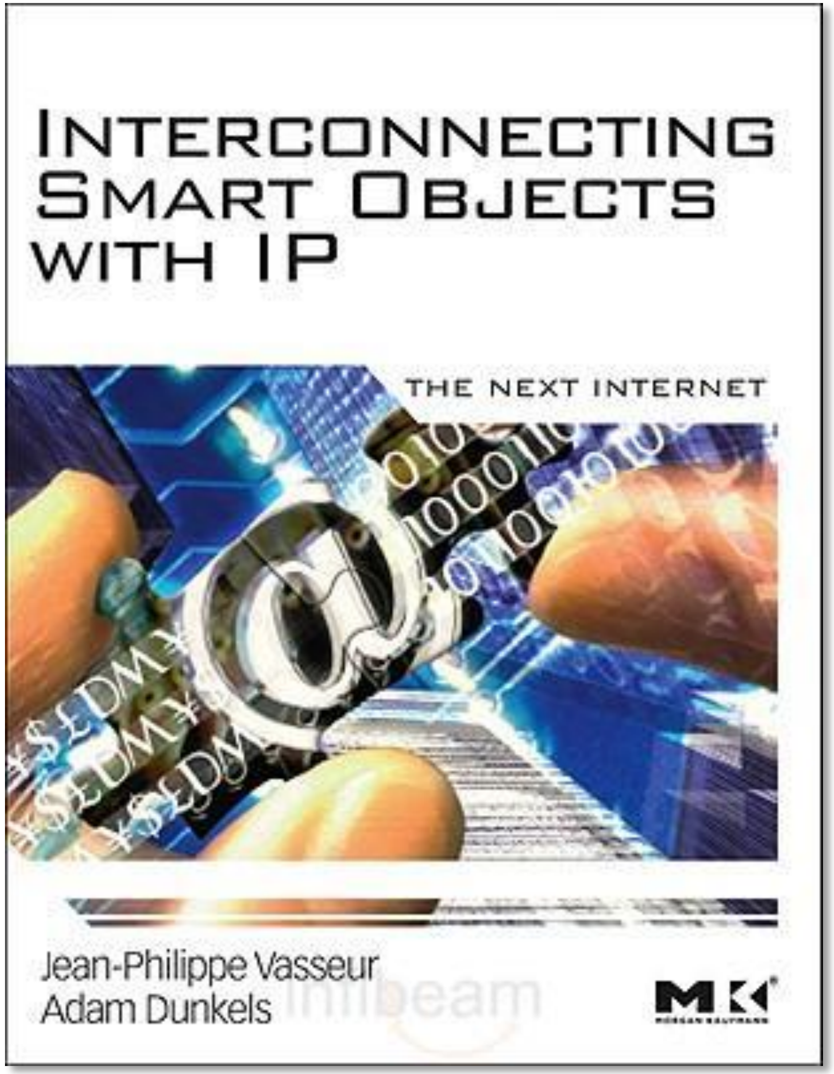



Conclusion

Conclusion

- IoT has many applications
  - Smart Grid, Green, Industrial, Connected building/homes, Smart Cities
  - There is a lot of momentum around using IP
- Progress in protocols covering various layers
  - IP-based technologies: 6Lowpan, RPL, CoAP, LWIG
  - IPSO alliance, ETSI
  - Adoption of IP by several other SDOs/alliance: Zigbee/IP for SE2.0, Bacnet, ….
  - RPL an important component of building large scale sensor networks
- RPL has the potential to be the foundation routing for “Things” across field areas

References



- Covers the trends in Smart Objects
- RPL protocol
- Detailed application scenarios
- Written by
  - JP Vasseur (Cisco Fellow)
  - Adam Dunkels (Inventor of Contiki O/S, uIPv6)
- Cisco Developers Network
  - IPv6 SDK
  - http://developer.cisco.com/web/cegd/overview




Q & A

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